NASA Conference Publication 2365

Applications of Tethers in Space

Volume 2

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General Research Corporation
McLean, Virginia

Proceedings of a workshop sponsored by the
National Aeronautics and Space Administration,
Washington, D.C., and George C. Marshall Space
Flight Center, Huntsville, Alabama, and held in
Williamsburg, Virginia
June 15–17, 1983

NASA
National Aeronautics
and Space Administration

**Scientific and Technical
Information Branch**

1985

PREFACE

The 1983 Applications of Tethers in Space Workshop was an important forum for diversity of scientific and engineering opinion about the prospective uses of tethers in space. The technical arguments, given in the resulting Workshop Proceedings, supporting the development of the Tethered Satellite System are carefully reasoned and thoroughly sound. The scientific uses of the new facility are striking in their importance and breadth. Overall, we are very impressed with the sheer enthusiasm which pervades the entire document. It is clear that this cooperative U.S./Italian project has struck many resonances with a broad range of potential users of space platforms.

In fact, we wonder if the support given to the Tethered Satellite System isn't an expression of technical pleasure derived from the quickening pulse of mankind's ability to explore and utilize space. The opportunity to conduct operations from multiple platforms orbiting Earth can be viewed as another liberation step in our ability to move freely throughout the solar system and, perhaps, even into deep space.

The presentations contained within the Workshop Proceedings consider many different applications. Some of the topics are clearly more mature, in a technical and scientific sense, than others. Yet, this is the time to have speculative thoughts and novel ideas. The passage of time and confrontations with technical and fiscal reality will winnow the collection into a harvest of rich technical productivity.

We commend these proceedings to the reader as an important document demonstrating both curent engineering and scientific perceptions concerning tethers in space and as a guide to many ideas whose time will come in the future.

Peter Banks
Carlo Buongiorno
1 December 1983

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FOREWORD

The "Applications of Tethers in Space" Workshop was held at Williamsburg, Virginia, on 15-17 June 1983. The workshop was sponsored by the Office of Space Transportation (OST) and Marshall Space Flight Center (MSFC) of the National Aeronautics and Space Administration (NASA). The goals of the workshop were:

- To provide a focus for, and a review of, technological opportunities and requirements for the application of tethers in space.
- To brief aerospace planners and specialists on the nation's space program plans for the Tethered Satellite System (TSS) and on NASA's current efforts for developing effective, tether applications.
- To delineate a data-base of methods, techniques, and technologies which may prove effective in the design and development of tether systems for use in the space program.
- To aid in planning OST's tether applications program by identifying applications technological needs and promising research topics and approaches.
- To insure that all parties involved are aware of significant programs in industry, academia, government and internationally which may be helpful in determining optimal tether roles for future space missions.

The workshop served to continue the dialogue between the tether community and the space program's planners, researchers, and operational staff. The focus for continuing this dialogue will be a tether research program which is being supported by NASA's Office of Space Transportation to begin in 1984. The goal of the research program is to develop an empirical data base for determining application optimal roles, procedures, and interfaces for a tether space program. This includes ground operations as well as on-orbit operations.

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This report contains copies of all the presentations given (Sessions I-IV) and the reports of the working group (Session V). In most cases, the presentations were made with overhead transparencies, and these have been published two to a page. The author's explanatory text is presented on the facing page.

1 December 1983
Washington, D.C.

TABLE OF CONTENTS

PAGE

VOLUME I

SESSION I - INTRODUCTION 1-1

Welcome; Orientation and Purpose 1-3
- William R. Marshall
Marshall Space Flight Center

Keynote Address 1-17
- Ivan Bekey
NASA Headquarters

SESSION II - TETHERED SATELLITE SYSTEM 2-1

Project Overview 2-3
- Jay Laue
Marshall Space Flight Center

Tether Deployment 2-21
- Donald Crouch
Martin-Marietta, Denver

Satellite Overview 2-35
- Gianfranco Manarini
PSN/CNR

Satellite System Description 2-57
- Marcello Vignoli
Aeritalia

SESSION III - FUNDAMENTALS AND APPLICATIONS 3-1

Tether Fundamentals 3-3
- Chris Rupp
Marshall Space Flight Center

Science Applications I 3-19
- Franco Mariani
University of Rome

Science Applications II 3-31
- James Murphy
NASA Headquarters

Electrodynamic Interactions 3-49
- Nobie Stone
Marshall Space Flight Center

PAGE

Transportation Applications I 3-67
- Joseph Carroll
California Space Institute

Transportation Applications II 3-79
- Enrico Lorenzini
Aeritalia

Artificial Gravity 3-95
- D. Bryant Cramer
NASA Headquarters

Constellations 3-109
- David Criswell
California Space Institute

Technology and Test 3-123
- Paul Siemers
Langley Research Center

"Where Are We Going With Tethers?" 3-129
- Professor Giuseppo Colombo
Harvard-Smithsonian

SESSION IV - PANEL CHAIRMEN SUMMARIES 4-1

Science Applications 4-3
- Bob Hudson
NASA Headquarters

Electrodynamic Interactions 4-11
- Dick Taylor
Harvard-Smithsonian

Transportation Applications 4-23
- Max Hunter
Lockheed

Artificial Gravity 4-39
- George Butler
McDonnell Douglas Astronautics Corporation

Constellations 4-51
- Frank Williams
Martin-Marietta-Michoud

Technology And Test 4-63
- Paul Siemers
Langley Research Center

PAGE

VOLUME 2

SESSION V - PANEL REPORTS 5-1

Science Applications - Franco Mariani, Bob Hudson 5-3

Electrodynamic Interactions - Dick Taylor, Nobie Stone 5-11

Transportation Applications - Max Hunter, Ernesto Vallerani 5-31

Artificial Gravity - George Butler, Bob Freitag 5-87

Constellations - Frank Williams, Giovanni Rum 5-163

Technology and Test - Col. Norman Lee, Paul Siemers 5-193

APPENDICES

A ATTENDEES A-1

B PANEL MEMBERSHIP B-1

C MEETING AGENDA C-1

D REFERENCES D-1

SESSION V

PANEL REPORTS

REPORT OF THE
SCIENCE AND APPLICATIONS PANEL

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SCIENCE AND APPLICATIONS PANEL

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SPACE SCIENCE AND APPLICATIONS

I. INTRODUCTION

Space Science and Applications has had an historical interest in the Tether Satellite System from its concept. The original proposal, by Colombo, et al. (1974) on Skyhook, was to carry out space science experiments at low altitudes. Thus, a most important aspect of future missions in the area of Space Science and Applications is for reflight of the present satellite system and the obtaining of additional scientific information. However, the panel considered more than just a continuation of present research. Many innovative ideas have been put forward, and are discussed in the sections below.

The panel did not consider space plasma physics in any depth, as this area of research is being covered by the Electrodynamic Interactions panel. The deliberations of the panel have been broken down into five main subheadings, (1) the exploitation of the present system and the need for repeat missions, (2) multiple payloads placed along the tether, (3) the extension of the present altitude limit to below 130 km, (4) the development of free-flying tether satellites for studying both the Earth's atmosphere and ionosphere and also for studying the planets, (5) a sub-tether.

II. EXPLOITATION OF PRESENT SYSTEM

Reflights of the present TSS configuration would involve no significant change to the launch and retrieval mechanism as presently conceived. We also envision only minor changes to the satellite. We have identified three areas of research that might be carried out:

(1) Aeronomy studies using the instrumentation which would be provided for the second mission. This instrumentation will be reflown in different orbital inclinations, for example, 28°, but at a different local time of the ascending mode, and/or a different season. Another

set of missions would involve reflights in polar orbit (65°-90°). One would probably add a particle spectrometer to the payload complement in order to obtain significantly new information. The length of the magnetometer boom would have to be increased and one would add a second fluxgate magnetometer.

(2) Gravity and magnetic potential mission. The TSS satellite body stripped of the aeronomy experiments could be used to fly both below and above the shuttle to obtain information on the magnetic field of the Earth. The satellite would need to have a magnetometer boom at the end of which would be placed two magnetometers, one scalar, one vector. This experiment would require a high precision altitude determination (GPS or similar transfer system). A gravity gradiometer would be flown inside the spacecraft sphere and referenced to the altitude reference point. It would also be desirable to place corner reflectors on the spacecraft for laser ranging from the shuttle or from the ground.

(3) Advanced sensors for geodynamics. Superconducting technology offers the promise of dramatically increased sensitivity and accuracy in magnetic and gravitational measurements. A very sensitive magnetic gradiometer could measure signals from the earth's core and crustal field, while cancelling most of the interference from external sources. The satellite would carry a space dewar containing liquid helium coolant for the superconducting vector magnetometer and magnetic and gravity tensor gradiometers. The entire satellite should be an non-magnetic as possible, with any essential magnetic sources physically separated from the sensor package. The tether would isolate the sensor from magnetic and gravitational interference from the space shuttle. The orientation of the sensors should be measured as accurately as possible. Future TSS missions incorporating such advanced magnetic and gravitational sensors, if flown periodically, would allow precise long term monitoring of the terrestrial magnetic crustal signatures and the geologically related gravitational gradients.

(4) Mapping and Remote Sensing. The tether satellite has the ability to place optical instruments at much lower altitudes than can be presently made feasible. There is the possibility, therefore, that much greater spectral or spatial resolution can be attained even with existing instruments. This area of work has not been actively investigated to date, but the panel felt that this was an area that should be examined in the future.

III. MULTIPLE PAYLOADS

Three applications of more than one satellite being placed on the same tether at different altitudes were identified:

a. Aeronomy. One of the difficulties in ionospheric and atmospheric research is to be able to distinguish changes in composition which are due to temporal effects from those due to spatial effects. A single satellite moving through the atmosphere cannot, in general, separate one from the other. What is required are several satellites moving in approximately the same altitude or spatial region. These satellites could either be strung along a tether released from the shuttle, or could be tethered together in a free-flying mode. Such satellites would contain mass spectrometers, devices to measure the wind direction, density determinations, instruments to obtain ion and electron temperature, instruments to determine the composition of the ambient ions.

b. Geodynamics. A multispacecraft tether would be used principally for the measurement of gravity and magnetic field and field gradients. These measurements could be performed both upward from shuttle and downward. The upward tether would enable measurements of the core magnetic field to be made, whereas the downward tether would enable measurements of the core field and local crustal gravity and magnetic anomalies to be made.

c. Remote Sensing. For many sensing measurements of the Earth, different angles of observations are required, e.g., if one wishes to measure height above the surface. The reflectivity, the emissivity and the scattering properties of surfaces are strongly dependent on the angle of viewing and it has been shown that by looking at different angles one can obtain more information about the scattering surface than from one angle. The proposed new application is to obtain these different angles by placing instruments along a tether, e.g., the shuttle could have one set of instruments while the tether satellite could have a similar set but at 100 km below the Shuttle. Both instruments would look at the same point of the ground, but, with a differing viewing angle.

IV. LOWER ALTITUDE MEASUREMENTS

An important attribute of the Tether Satellite System is its ability to deliver payloads or instruments to lower altitudes than can be achieved by free-flying satellites in stable orbits. This capability appeals to a wide range of scientific disciplines. In geodynamics, design of the spacecraft will require special attention and innovative spacecraft designs. Solutions to these problems are (1) to optimize the present design to reduce the minimum altitude including thermal shielding, (2) to look at the advantages of having the tether at 130 km altitude at the pole, thus bringing the satellite to 115 km altitude at the equator, or (3) consider a completely new design. A nacelle shape, for example, where the flow inside the throat would be sampled might be a useful approach. At about 120 km the mean free path of the atmosphere becomes equal to the dimensions of a typical spacecraft and in this transition region, different experimental approaches and different interpretations will be required. Consideration should be given to the lowering of a sub-satellite from the main tether satellite, perhaps with only a single instrument, to sample the atmosphere below 120 km.

V. TETHERED AUTONOMOUS MULTIPLETS

Although the period of time achievable in a Shuttle mission is adequate for many scientific studies, eventually, the length of the mission should be extended in order that synoptic analysis of processes in the atmosphere can be achieved. This would require the development of autonomous multiplets of satellites joined with tethers. A particular application of this technique would be in planetary missions in which detectors could be placed as close to the surface as is reasonable yet the main spacecraft could be placed at an altitude where slight anomalies in the planetary gravity field would not divert the satellite into the planets surface. This type of mission would appear to be feasible only for planets with little or no atmosphere.

For aeronomy studies, one can conceive of two modes of multiplet mechanics. In the first, two spacecraft will be placed about one scale height apart, one vertically beneath the other. In the second mode, the total system would spin around the center of mass of the two spacecraft. In this mode one would be continuously sampling the altitude profile of the atmosphere or ionosphere. This system would enable effects due to temporal and spatial variability of the atmosphere or ionosphere to be separated.

VI. SUB-TETHER

There are important applications to atmosphere physics, in which a sub-tether aboard a satellite tethered to the Shuttle would enable a small sub-satellite to be deployed downward or upward from the main satellite. Vertical structure of the atmosphere could be studied in detail if one had a system of this form. Previous studies of vertical structure have relied on two satellites in independent orbits, or the precession of one satellite, and it is difficult in either of these cases, to separate spatial from temporal variations. Knowledge of vertical structure near the TSS satellite would allow information to be determined concerning the diurnal variations at the turbopause altitude, the nature of the temperature variations, variability associated with waves, windshear and a number of other parameters. Measurements of the vertical structure at these altitudes is fundamental to defining this region.

The sub-tether could also be used to release an inflatable passive sphere. By radar-tracking the sphere, the neutral density of the atmosphere, down to an altitude of 80 km, can be obtained. Release from a tether satellite would allow density profiles to be derived in regions inaccessible to rocketsounde sensors, as well as near the re-entry path of the Shuttle vehicle, and in regions where density measurements are needed for the Aero-assist program, etc.

N85-20363

REPORT OF THE
ELECTRODYNAMIC INTERACTIONS PANEL

ELECTRODYNAMIC INTERACTIONS PANEL

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I. INTRODUCTION

This report summarizes the results of discussions among the members of the Electrodynamics Panel of the Applications of Tethers in Space Workshop held at Williamsburg, VA, June 15-17, 1983. This panel considered a range of scientific and technological uses of the electrodynamic tether, identified eleven areas of particular concern, and made specific recommendations on the research required in this area in the immediate future.

This panel was particularly impressed by the wide range of opportunities provided by the electrodynamic tether to more fully understand the generation of waves in plasmas, the behavior of field aligned currents, the behavior of large body-space plasma interactions, and for process simulation, using the electrodynamic tether to study processes and phenomena relevant to solar system and astrophysics plasma physics. The electrodynamic tether offers a means of study and experimentation in space which will provide a rich yield in new scientific results and will enhance our understanding of space plasma physics. It also has promising technological applications (e.g., the generation of electrical power and thrust) which may be highly significant to future space operations.

II. ADVANCED APPLICATIONS OF ELECTRODYNAMIC TETHERS IN SPACE

Applications identified and recommended by the panel for further investigation are listed below in Table 1 and discussed on the pages which follow. Following the descriptions, the primary concerns relating to these applications are identified and recommendations are presented.

TABLE 1

ADVANCED APPLICATIONS OF ELECTRODYNAMIC TETHERS IN SPACE

I. Technology
  1. Power Generation (Hi-I, Lo-V*)
  2. Thrust Generation
  3. ULF/ELF Communication
  4. Energy Storage
  5. In-Plane Sheet Plasma Contactor
  6. Thrust Generator for Planetary Capture
  7. Interplanetary Propulsion (solar wind)

* ~1 kW

TABLE 1

ADVANCED APPLICATIONS OF ELECTRODYNAMIC TETHERS IN SPACE (CONT.)

II. Science
  1. Generation of Waves in Plasmas
  2. Field Aligned Currents
  3. Large Body Plasma Interactions (Sheath and Wakes)
  4. Process Simulation (Solar System and Astrophysics Plasma Simulator)

III. TECHNOLOGY APPLICATIONS

1. Tether Power Generation

The electrodynamic characteristics of a conducting tether in earth orbit can be utilized to generate useful electric power for a number of applications. This is obtained from the $q\vec{V} \times \vec{B}$ emf, as shown in Fig. 1, and at the expense of vehicle velocity. Therefore, it is necessary to use some means of propulsion to reboost the vehicle periodically.

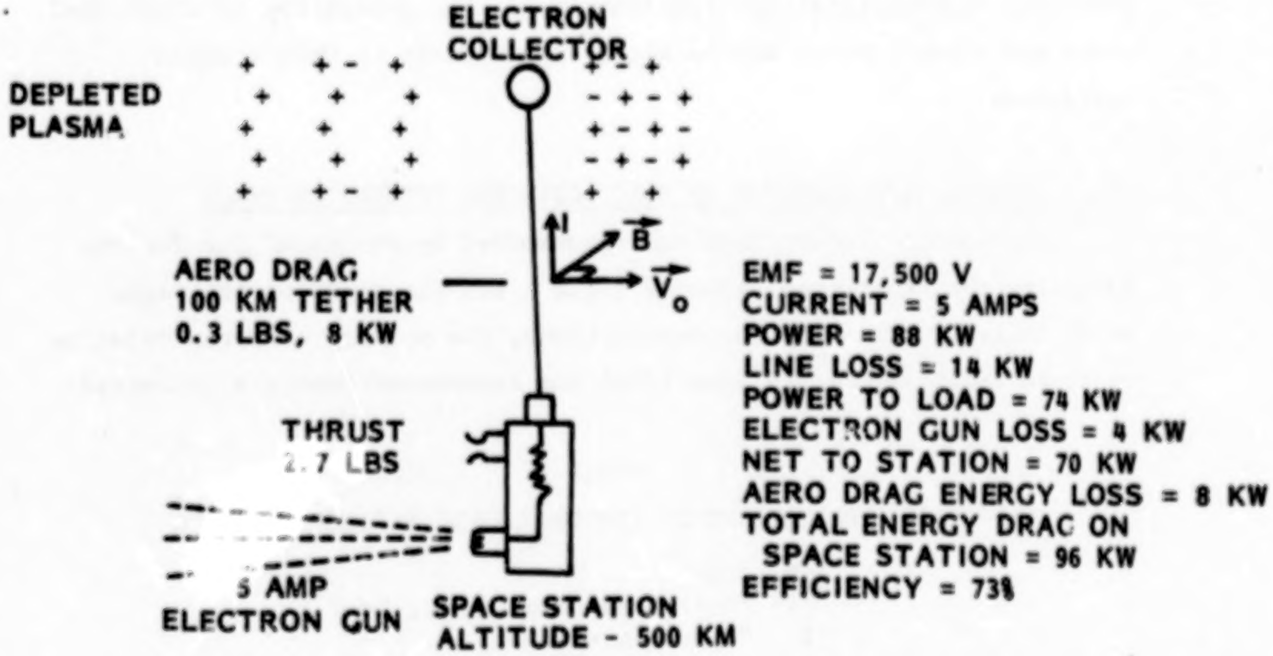
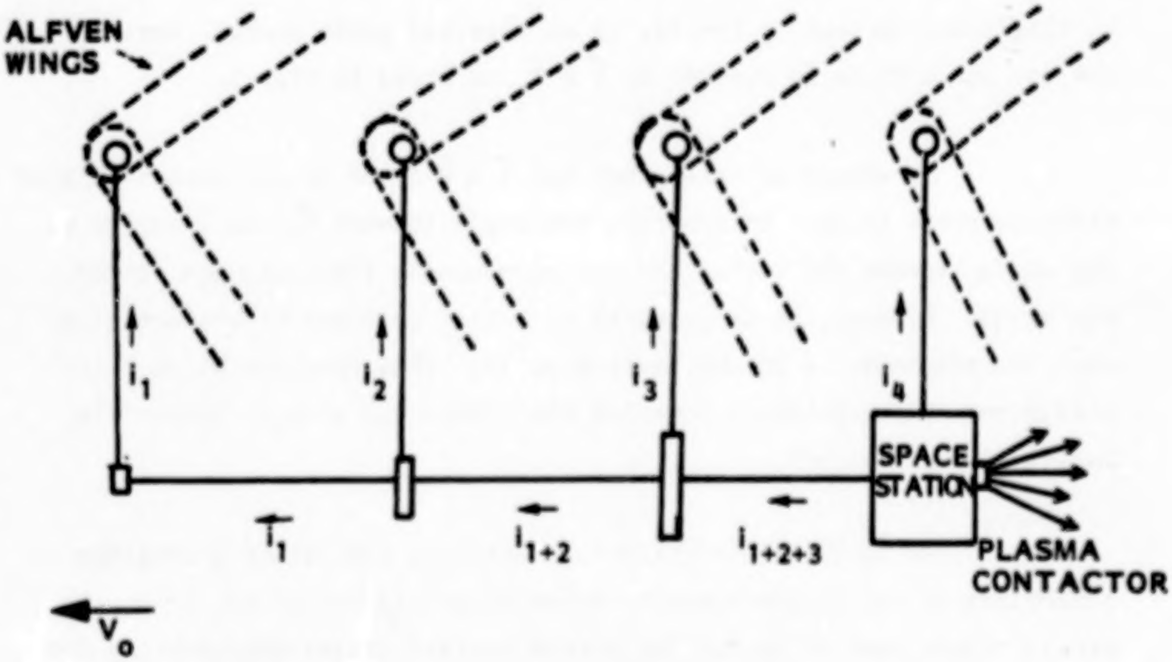

ELECTRON COLLECTOR
DEPLETED PLASMA
AERO DRAG
100 KM TETHER
0.3 LBS, 8 KW
I
$\vec{B}$
$\vec{V}_o$
EMF = 17,500 V
CURRENT = 5 AMPS
POWER = 88 KW
LINE LOSS = 14 KW
POWER TO LOAD = 74 KW
ELECTRON GUN LOSS = 4 KW
NET TO STATION = 70 KW
AERO DRAG ENERGY LOSS = 8 KW
TOTAL ENERGY DRAG ON SPACE STATION = 96 KW
EFFICIENCY = 73%
THRUST 2.7 LBS
5 AMP ELECTRON GUN
SPACE STATION ALTITUDE - 500 KM

Figure 1. Operating Characteristics

The tether power generator has several advantages over conventional power sources. For example, it is 2.5 to 3 times as efficient as the best possible fuel cells in terms of fuel utilization and it is not subject to day/night cycles as are all solar arrays. The required reboost forces are so small that on a manned space station, the orbit can be maintained by using a resistojet fueled with life support effluent (at the rate of approximately 2.5 kW/astronaut).

Although special applications, such as high energy particle beam accelerators, may need the high voltages attainable from long tethers (100 km produces approximately 20 to 40 kV), it is apparent that for general utility power for a space station or space platform a lower voltage, high current source is more desirable. This implies shorter (approximately 10 km) higher conductivity tethers. Figure 2 is an example of how this requirement might be approached.



(HIGH CURRENT, ~100 A, INTERMEDIATE VOLTAGE, ~1 kV)

Figure 2. Tether Power Generation

The contact area with the ionospheric plasma is maximized by the multiple contact points using a tether "constellation" configuration, therefore, allowing a larger total current to flow from the ionosphere through the tether power generator. By deploying the tethers upward, passive collection of electrons can be made and the electrons actively emitted at the space station.

Shorter tethers have the advantage of minimizing the high voltage, insulation, and material problems inherent in very long tethers. In addition, they may be semi-rigid, since they do not require retrieval. In this case, a "beam builder" may be used to erect the tether constellation and as much insulation as needed could be applied to the structure.

2. Tether Thrust Generation

The electrodynamic characteristics of an orbiting conducting tether can also be utilized to generate thrust. This is essentially the reverse of the power generation process (similar to a motor/generator). In this case, current is forced, by an external power source, against the emf and a force is created by $\vec{I} \times \vec{B}$, as shown in Fig. 3.

It should be noted that the $\vec{I} \times \vec{B}$ force is not always aligned with the orbit track. In general, the angle between $\vec{V_0}$ and $\vec{F}$ varies as the angle between the tether and the geomagnetic field changes around the orbit. However, it is possible to select portions of the orbit so that the alignment is at the desired angle. This fact can be used to attain not only raising or lowering the orbit, but also to change the inclination of the orbit.

As indicated in following sections, the thrust generation capability of the electrodynamic tether is not limted to use in earth orbit; it may also be useful for interplanetary travel and breaking for planetary encounter.

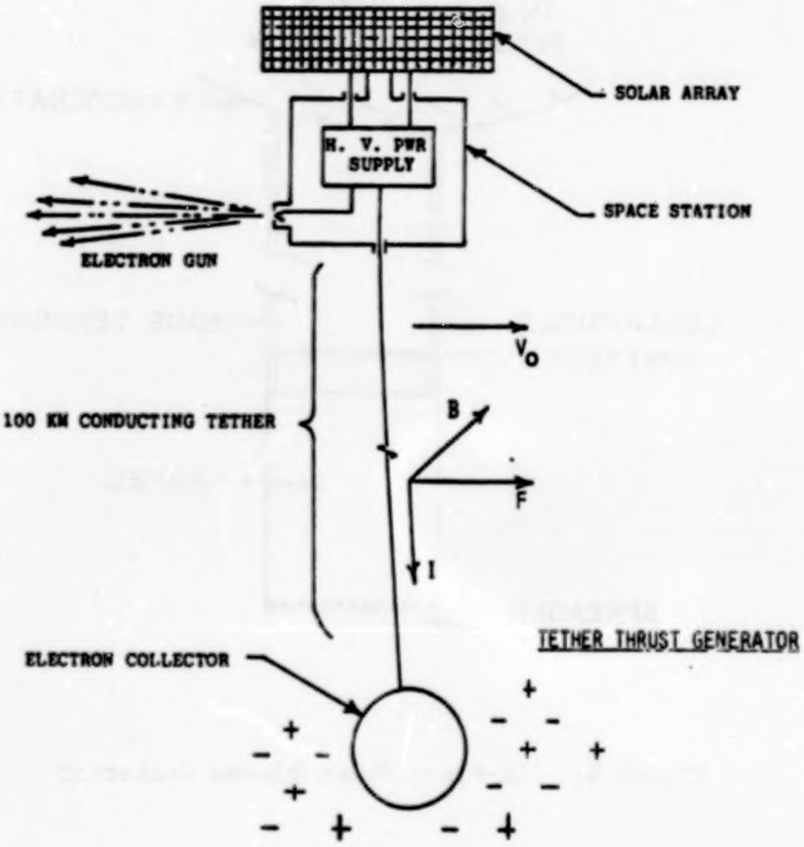

SOLAR ARRAY
H. V. PWR SUPPLY
SPACE STATION
ELECTRON GUN
V_0
100 KM CONDUCTING TETHER
B
F
I
TETHER THRUST GENERATOR
ELECTRON COLLECTOR

Figure 3. Tether Thrust Generator

3. In-Plane Sheet Plasma Contactor

As an alternative to metal balloons and plasma contactors, the use of flat metallized panels should be considered. Such a contactor could be based on the well developed Heliogyro blade design and would be deployed by gravity gradient rather than rotation.

Dual edge tendons and spreader bars would support the panels normal to field lines, and parallel to the orbital velocity vector to keep aerodynamic drag low in low inclination orbits (see Fig. 4).

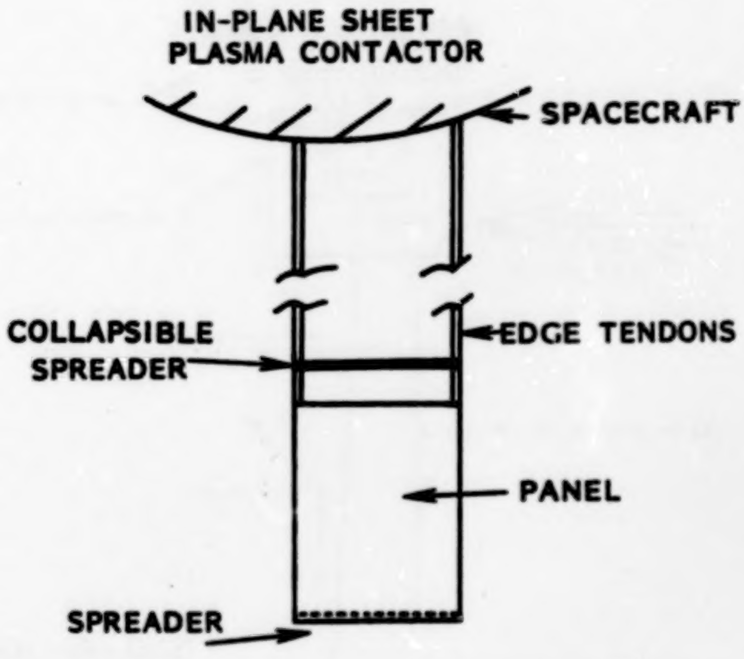

IN-PLANE SHEET
PLASMA CONTACTOR
SPACECRAFT
COLLAPSIBLE
SPREADER
EDGE TENDONS
PANEL
SPREADER

Figure 4. In-Plane Sheet Plasma Contactor

4. Thrust Generator for Planetary Capture

In lieu of chemical propulsion, use of a conducting tether for electrodynamic braking for planetary orbit insertion should be considered. A spacecraft designed in halves would be separated upon planetary approach while remaining connected by a conducting tether used in the thrust mode. Upon capture, the spacecraft halves would be rejoined for normal orbital operations. This approach is probably applicable only to planets with relatively strong magnetic fields and further study is required to assure that sufficient braking is available for capture in a single pass (see Fig. 5).

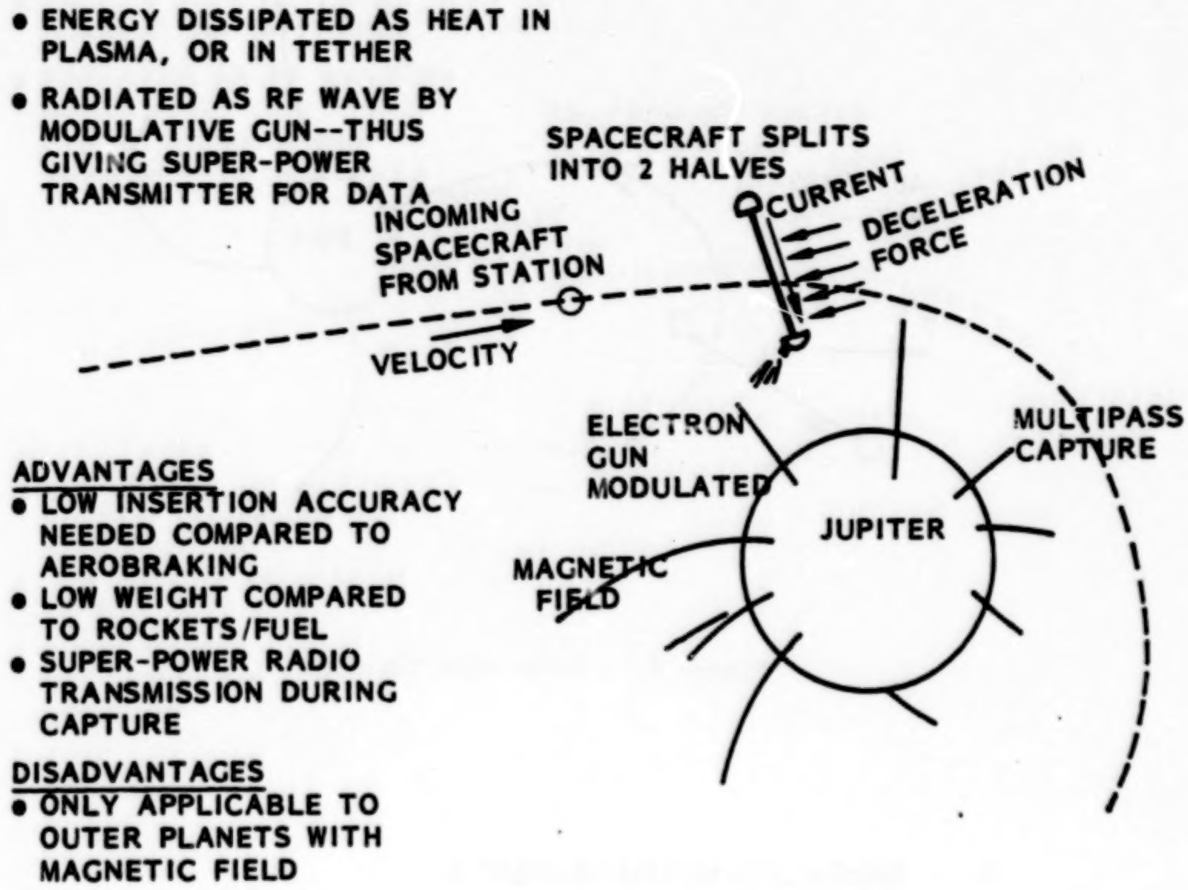

• ENERGY DISSIPATED AS HEAT IN PLASMA, OR IN TETHER
• RADIATED AS RF WAVE BY MODULATIVE GUN--THUS GIVING SUPER-POWER TRANSMITTER FOR DATA
SPACECRAFT SPLITS INTO 2 HALVES
CURRENT
DECELERATION FORCE
INCOMING SPACECRAFT FROM STATION
VELOCITY
ELECTRON GUN MODULATED
MULTIPASS CAPTURE
JUPITER
MAGNETIC FIELD
ADVANTAGES
• LOW INSERTION ACCURACY NEEDED COMPARED TO AEROBRAKING
• LOW WEIGHT COMPARED TO ROCKETS/FUEL
• SUPER-POWER RADIO TRANSMISSION DURING CAPTURE
DISADVANTAGES
• ONLY APPLICABLE TO OUTER PLANETS WITH MAGNETIC FIELD

Figure 5. Electrodynamic Braking for Planetary Capture

5. Use of Electrodynamic Tethers for Interplanetary Transportation

The solar wind is a magnetized plasma that flows radially outward from the sun with a velocity of about 400 km/sec. More than a decade ago, Alfven (1972) proposed that the motion of this magnetic field could be used as a propulsion source for interplanetary spacecraft. Because the solar wind magnetic field is 5×10^{-5} Gauss, the electric field seen by an interplanetary spacecraft is 2 V/km. Alfven suggested that a spacecraft with a long electrodynamic tether (say 500 km) could be propelled by the $\vec{I} \times \vec{B}$ force on the tether, or could use the power extracted from the solar wind as an energy source for ion thrusters. In principle, such a spacecraft could accelerate to the solar wind velocity of 400 km/sec (see Fig. 6).

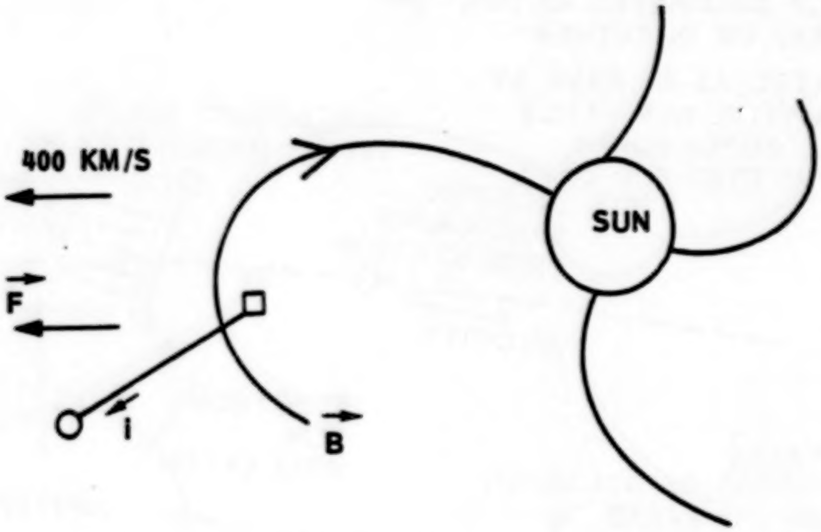


Figure 6. Solar Wind Velocity

6. ULF/ELF Communications Antenna

Use of a conducting tether for communications in the ULF/ELF bands is an attractive potential application requiring further study and experimentation to demonstrate its effectiveness. Such antennas could be self or externally powered. Communication rates are low (about 100 bits/min) but the transmissions will propagate easily through sea water or the ground. Recent studies have revised our understanding of the propagation mechanisms at these frequencies (see Table 2). Further studies are required to identify an approach to optimize these mechanisms for communication purposes.

TABLE 2
EM PROPAGATION MECHANISMS

- AT FREQUENCIES SMALLER THAN f_{mi} (ABOUT 60 HERTZ IN THE CASES OF OUR INTEREST), O WAVE IS CALLED GUIDED ALFVEN WAVE AND X WAVE OMNIDIRECTIONAL ALFVEN WAVE.
- FOR PRAPAGATION $\parallel$ B , O WAVE IS LEFT-HAND CIRCULARLY POLARIZED AND X WAVE RIGHT-HAND CIRCULARLY POLARIZED.
- FOR PROPAGATION $\perp$ B , O WAVE DOES NOT PROPAGATE, X WAVE PROPAGATES AND GENERATES HALL OSCILLATIONS IN PLASMA (ACOUSTIC-LIKE VIBRATIONS WHERE PRESSURE IS MAGNETIC AND PROPAGATION VELOCITY IS V_A).
- GUIDANCE OF O WAVES , ALONG THE LINE OF FORCE OF THE GEOMAGNETIC FIELD, IS ACTIVE FOR A LENGTH NO LARGER THAN $_{g_1}\ell_{max} \leq \frac{f_{mi}}{f} \lambda$ WHERE $\lambda_A = \frac{v_A}{f}$
- AT HIS END, WHEN GUIDANCE CEASES, THE LINE FUNCTIONS AS AN END-FIRE ANTENNA THAT RADIATES A NARROW BEAM WHOSE WIDTH IS $(f/f_{mi})^{1/2}$
- THE X WAVE BEHAVES SIMILARLY, FOR PROPAGATION $\parallel$ B .

7. Potential Environmental Impact of Electrodynamic Tethers

Electrodynamic tethers will be a source for ELF/ULF radiowaves. Even if the tether is used for power generation or thrust, this radiation will be generated whenever the tether current is varied. These radiowaves will interact with the earth's plasma environment in ways that are not yet fully understood. However, there is evidence that man-made ELF/VLF can affect the geomagnetically-trapped Van Allen radiation belts. The recent SEEP satellite mission showed that Navy VLF transmitters can precipitate trapped electrons, and power-line radiation at high latitudes may also affect the radiation belts. Because the electrodynamic tether is located within the ionosphere, ELF/ULF radiowaves generated by it will be injected into the magnetosphere more efficiently than the present ground-based man-made sources. Evaluation is needed of the inadvertent environmental effects of ELF/VLF radiowaves generated when electrodynamic tethers are used for power or thrust.

IV. SCIENTIFIC APPLICATIONS

The electrodynamic tether offers a vast and very rich opportunity for scientific investigation. This section does not attempt to list all possible experiments--but, rather, to provide a few examples in several of the more obvious areas of study.

1. Generation and Propagation of Waves in Plasmas

A large number of wave modes can be excited and studied, ranging from ULF/ELF, which may be useful for communication, to various plasma and hydromagnetic modes, which are of scientific interest because of their frequent occurrence in solar system plasma physics and of technological interest because of their impact on tether power/thrust generation. For example, Alfven waves will serve to disperse the space charge deposits at the tether ends, thereby creating a better contact with the ionospheric plasma, while high frequency plasma waves may heat the plasma and produce power losses.

Almost without exception, the investigation of wave generation and propagation requires remote observations from a free-flyer. In the case of ULF/ELF propagation and communication studies, the radiated power should be measured in the tether near field by a free-flyer and by ground-based facilities in order to determine the propagation characteristics through the ionosphere to the ground.

2. Field Aligned (Birkeland) Currents

Once the electrodynamic tether has deposited charge of opposite sign at its ends, the regions of charge must recombine. It is thought that this will occur via currents traveling along the geomagnetic lines of force down into the E-regions of the ionosphere where collisions with neutrals allow migration across the field lines to close the circuit, as shown in Fig. 7.

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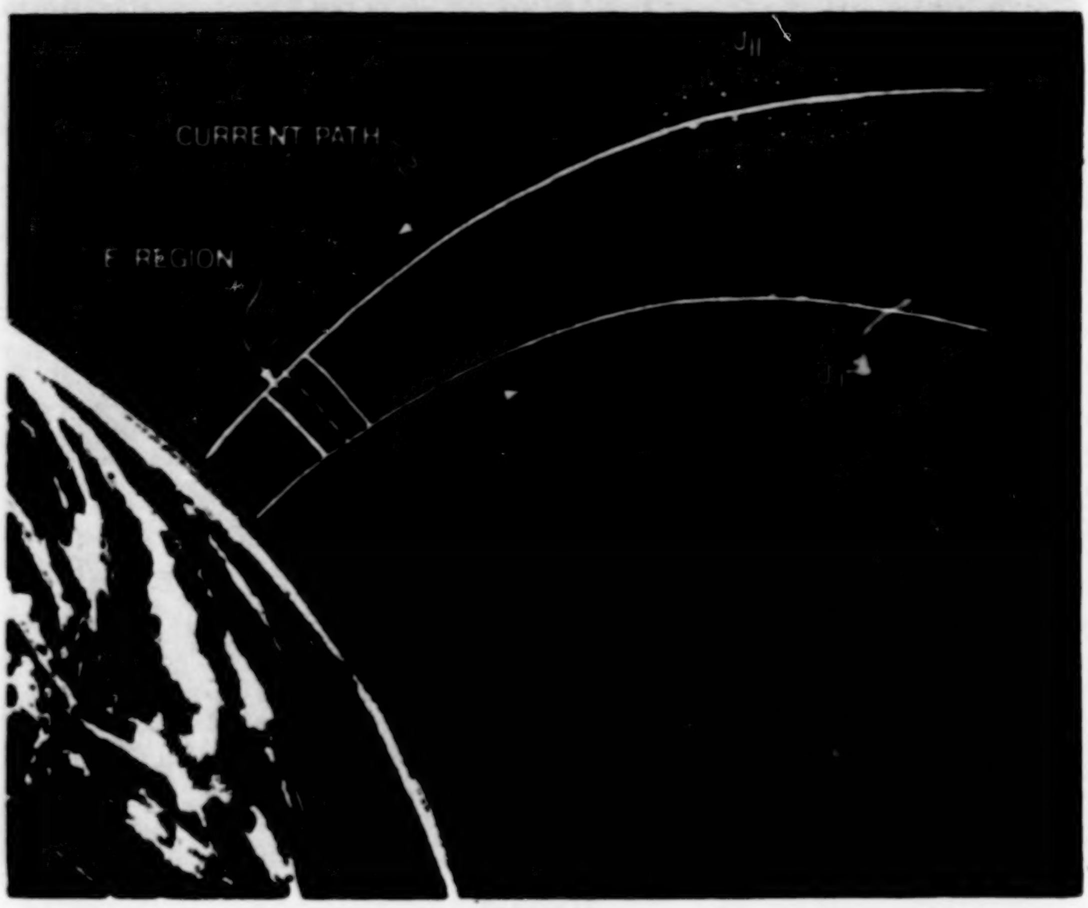

Figure 7.

This process is of scientific interest because of the importance of Birkeland current systems in the earth's auroral zone, in the sun, and in various planetary systems, such as Jupiter and Saturn. Such current systems may also generate instabilities, radiate certain hydromagnetic wave modes, and create double layers--all of which are frequently encountered in nature. Notice for example, the great similarity between the tether generated system in Fig. 7 and the type of system thought to be generated by the interaction of the Jovian satellite IO with the Jovian magnetosphere shown in Fig. 8.

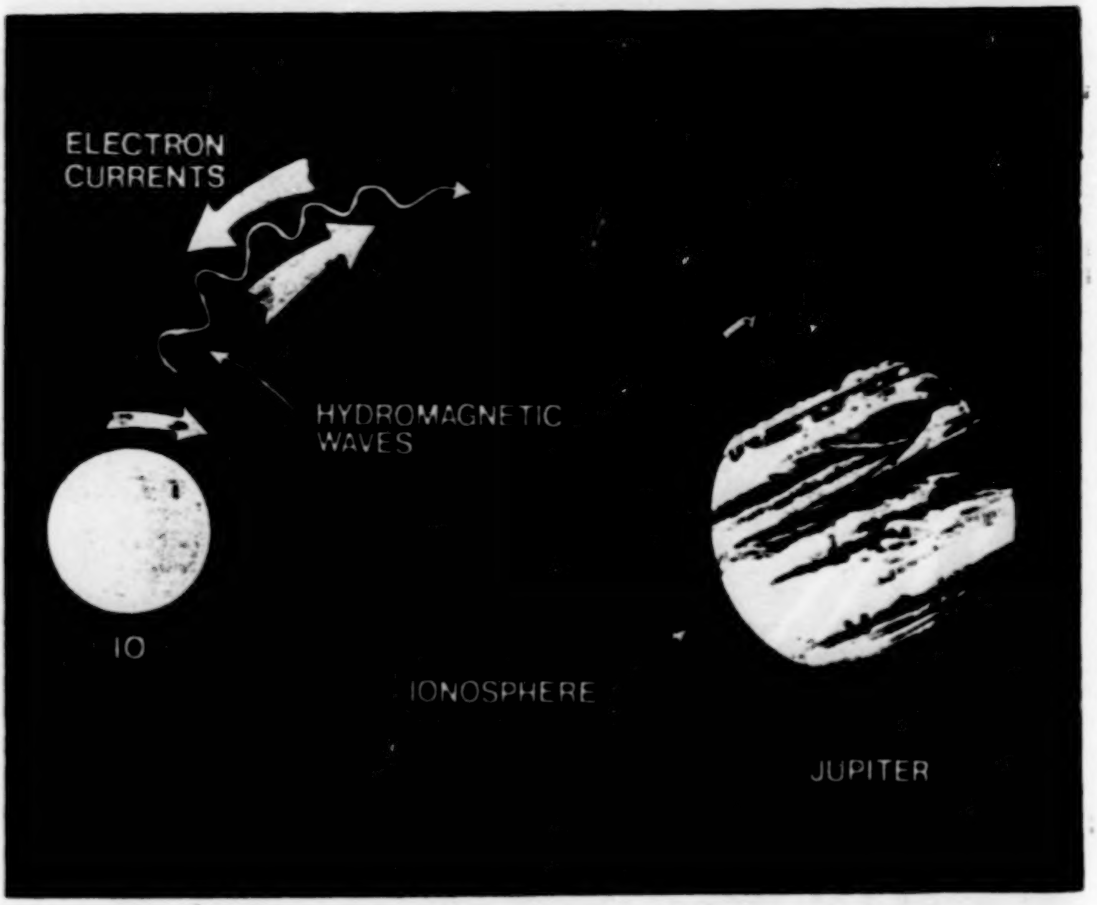

Figure 8.

3. Large Body Plasma Interactions (Sheath and Wakes)

The plasma flow interaction with large bodies in space is of both scientific and technological interest. It is a necessary part of understanding the environment of any large structure in space, such as a space station or space platform, and it is (as it occurs for artificial bodies orbiting within the ionosphere) qualitatively similar to certain interactions of space plasmas with natural bodies in the solar system. Such interactions, in fact, are extremely common in nature since plasmas exist throughout the observed universe and they flow past various types of obstacles. Therefore, such patterns occur in earth orbit, in solar system plasma physics, and in astrophysics.

The investigation of certain examples of flow interactions (large conducting/nonconducting bodies, magnetic bodies, etc. in a supersonic-subAlfvenic flow) can be studies in earth orbit with tethered

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test bodies and diagnostic instruments mounted on booms, on tethered instrument packages, and on free-flyers as shown in Fig. 9.

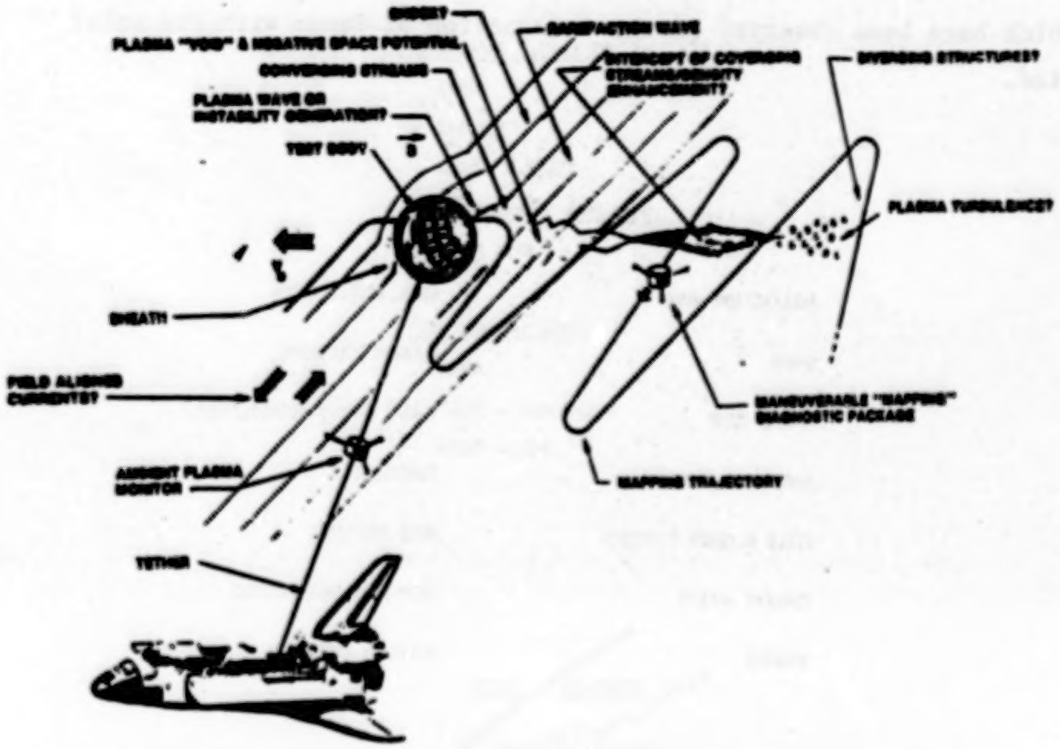
SHOCK?
RAREFACTION WAVE
PLASMA "VOID" & NEGATIVE SPACE POTENTIAL
CONVERGING STREAMS
INTERCEPT OF CONVERGING STREAMS/DENSITY ENHANCEMENT?
DIVERGING STRUCTURES?
PLASMA WAVE OR INSTABILITY GENERATION?
TEST BODY
$\vec{B}$
PLASMA TURBULENCE?
SHEATH
FIELD ALIGNED CURRENTS?
MANEUVERABLE "MAPPING" DIAGNOSTIC PACKAGE
AMBIENT PLASMA MONITOR
MAPPING TRAJECTORY
TETHER

Figure 9. Orbital Plasma Flow Interaction Experiment

4. Process Simulation

Process simulation is the investigation of certain physical mechanisms or processes, which occur in natural phenomena. It makes use of the concept of qualitative scaling which requires only that scaled quantities which are much greater than unity in space remain so in the scaled experiment--but not necessarily to the same order of magnitude (i.e., $P_{Space} \gg 1$ then $P_{Exp} \gg 1$). Likewise, the inequality must be preserved for quantities which are much less than unity (i.e., $P_{Space} \ll 1$ then $P_{Exp} \ll 1$). Only when quantities are on the order of unity, they must be closely scaled (i.e., $P_{Space} \approx P_{Exp}$).

The range of plasma and electromagnetic processes which occur both in the solar system and in earth orbit is surprisingly large, as shown in Table 3. Tables 4 and 5 indicate where these processes have been observed in nature, while Fig. 10 shows a schematic of effects which have been observed in the interaction of Venus with the solar wind.

TABLE 3
PLASMA PHENOMENA

RAREFACTION WAVE
SHOCK
PLASMA VOID
CONVERGING STREAMS
FIELD ALIGNED CURRENTS
CURRENT SHEETS
SHEATHS

LOCAL ACCELERATION
RUNAWAY ELECTRONS
PLASMA WAVES/INSTABILITIES
TURBULENCE
MASS ADDITION
BEAM-BEAM INTERACTIONS
BOUNDARY LAYERS

TABLE 4
EXAMPLES OF MASS ADDITION TO AMBIENT SPACE PLASMAS

MASS ADDITION -- SLOW AMBIENT FLOW
Io
EUROPA
DIONE
TITAN

MASS ADDITION -- HIGH SPEED AMBIENT FLOW
VENUS
COMET

MASS ADDITION -- OTHER
SUN
EARTH

TABLE 5

OCCURRENCE OF PLASMA WAVES/INSTABILITIES

BROADBAND TURBULENCE

EARTH
JUPITER
SATURN
VENUS
SOLAR WIND

ION ACOUSTIC WAVES

TITAN
VENUS -- IONOSHEATH
VENUS -- TAIL

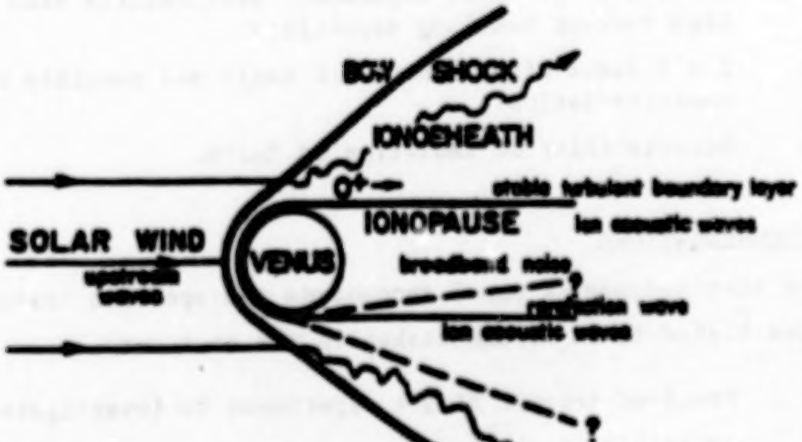
BOW SHOCK
IONOSHEATH
O+
stable turbulent boundary layer
IONOPAUSE
ion acoustic waves
SOLAR WIND
upstream waves
VENUS
broadband noise
?
rarefaction wave
ion acoustic waves
?

Figure 10. Effects in Interaction of Venus and Solar Wind

The study of such processes in earth orbit will increase our understanding of their behavior. This understanding can be extrapolated to explain measurements made during planetary missions much the way our understanding of Earth's magnetosphere was used to enhance our understanding of planetary magnetospheres.

V. TECHNOLOGY AND SCIENCE CONCERNS

The panel identified eleven specific areas of concern in the potential applications of the electrodynamic tether. A primary concern remains the development of a coupling mechanism between the tether ends and the surrounding medium; particularly in the very high current applications recommended herein for power and thrust generation. Tether materials and high voltage technology also require specific attention.

1. Tether materials (strength, conductivity, insulation, etc.)
2. High voltage technology
3. Spacecraft charging
4. Variations in power with tether angle and magnetic field variations
5. Impedance of collection mechanism and return circuit
6. Radiation losses along the line
7. Collection body properties (e.g., effect of size on radiation and alternate collectors)
8. Coupling with ionosphere; plasma drag and wake
9. Emitter properties; impedance, particularly with respect to high current handling capability
10. I x B force effect on tether angle and possibly orbit characteristics
11. Detectability of radiation on Earth.

VI. RECOMMENDATIONS

The electrodynamics panel recommends the specific research activities listed below be undertaken in the near term.

- Proof-of-concept flight experiment to investigate plasma contacting devices
- Further development of the theory for:
  - Formation and characteristics of Alfven wings
  - Radiation of higher frequency modes
  - ULF/ELF radiation and propagation through the ionosphere to ground
- Free flyer (with plasma and wave diagnostics) to measure wave emissions and plasma parameters in the near field of the tether/satellite

- **Ground based measurements of ULF/ELF emissions**
- **Laboratory investigation of:**
  - **Plasma wakes and electrodynamic drag and effect of potential**
  - **Optimization and current capacity of charge emission and plasma bridge devices.**

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REPORT OF THE
TRANSPORTATION PANEL

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TRANSPORTATION PANEL

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I. INTRODUCTION TO TRANSPORTATION SECTION

This section covers eleven tether applications for space transportation (Fig. 1). The first seven transfer momentum between two masses at the tether tips, and the remaining four use tethers for controlled interaction with the environment.

	MOMENTUM TRANSFER TETHERS		ESTIMATED PRACTICALITY
	Operation	Deployer On:	
1	Payload Boost	Orbiter	High
2	Upper Stage Boost		High
3	E.T. Deboost		Medium
4	Shuttle Deboost		High
5	Shuttle Docking	Space Station	Medium
6	Payload & OTV Boost		Medium
7	Payload Boost	Upper Stage	Medium
	ENVIRONMENTAL INTERACTION TETHERS		
8	Lunar Assist & Eccentricity Change		?
9	Aero-Maneuvering by Remote "Sail" or "Kite"		High
10	Electrodynamic Deceleration		?
11	Lunar & Planetary Applications		?

Figure 1. Transportation Applications of Tethers

Momentum transfer tethers typically provide considerably lower Delta-Vs than rockets, but they can use as a reaction mass objects that have already served other functions and may later be of use in other ways (e.g., orbiters).

Tethers are most clearly useful where opposite momentum changes are desired at the two tip masses, but can also pay for themselves by eliminating a need for rocket guidance systems, or by allowing space-station-based high I_{sp} thrusters to displace lower I_{sp} propellant use by free flyers.

Tether stresses scale with tether length, so halving the required Delta-V allows for a fixed tether mass to handle four times as much payload. As a result, for small enough in-plane orbital transfers (under about 300-600 fps), tethers require less dedicated mass than rockets and can thus pay for themselves in one use.

Applications 1-3 use a shuttle-based tether to boost payloads and upper stages, or to boost the orbiter by deboosting the External Tank. The same deployer hardware may serve all three applications. To save time and reduce the deployer size, mass, and cost, these shuttle-based applications might dispose of the tether after use rather than retrieving it.

Applications 4-6 all use a space station-based tether to deboost or dock with a shuttle, or to boost payloads. Tether operations with Delta-Vs up to several thousand feet per second may be justified, since the tether system mass can amortize itself over many uses.

Application 7 is upper-stage-based and boosts payloads while deboosting the used stage (and helping recover it for reuse).

Applications 8-11 use a tether for controlled interaction with the environment. One example is to use a lunar assist to add angular momentum to an object, and then circularize its orbit at GEO by active dissipation of the excess energy associated with an eccentric orbit (8). Another example is using a tether to transfer aerodynamic drag and lift from a remote "sail" or "kite" to a spacecraft at higher altitudes (9); this may allow larger orbital reusable OTVs by electrodynamic tether drag (10). Lunar and planetary applications (11) include reduction of the effects of mascons on low-orbiting sensors, electrodynamic deceleration of planetary probes, and a lunar "space elevator" that supports itself by reaching past L1.

Some other "tether-assisted transportation" concepts are more apropos to other sections. These include stationkeeping by electrodynamic tether or by a remote tethered thruster (to isolate contamination); and transport within a tethered constellation by hoist, elevator, or tram-like devices.

The following pages contain short sections discussing each application. The section concludes with the recommendations of the panel. An appendix is included with additional papers presented at the panel meetings.

II. APPLICATIONS

Shuttle Delivery of Payloads to Higher LEO Orbits (Figs. 2 and 3)

This concept involves deploying a payload upwards from a shuttle and releasing it near the apogee of an eccentric shuttle orbit. Assuming that the payload/orbiter mass ratio is 1:6, this operation raises the payload apogee by 6/7 of the tether length, and the payload perigee by 6-12 times the tether length, depending on whether the tether is hanging or swinging. The orbiter's apogee and perigee both shift downward, by 1/7 and 1 to 2 tether lengths.

- BENEFITS: CAN REACH ORBITS CURRENTLY UNREACHABLE
- EXTENDS ALTITUDE AND PAYLOAD DELIVERY CAPABILITY TO HIGHER POLAR ORBITS
- PRACTICALITY: HIGH
- COST BENEFIT: ?
- OPERATIONAL REQUIREMENTS

Figure 2. Shuttle Delivery of Payloads to Higher Orbits

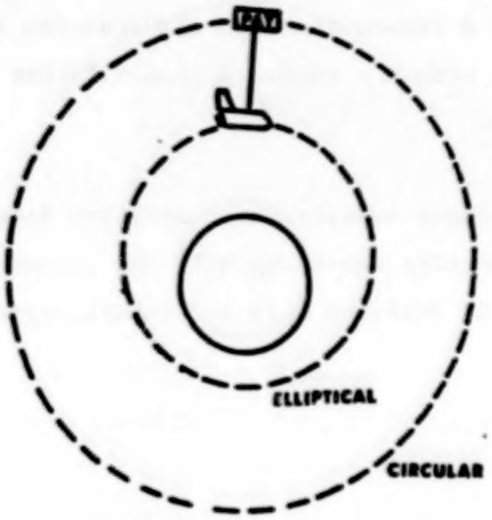


Figure 3. Placing Satellites in High LEO from Elliptic Shuttle Orbit

Such tether operations allow delivery of large payloads to higher orbits than otherwise possible even with OMS kits. The required tether deployer should be more compact than OMS kits, and should allow roughly twice as much gain in service altitude for a given reduction in payload. This is because standard STS operations involve an apogee boost, perigee boost, and perigee deboost, all of which increase mile-for-mile with service altitude. Tether operations require radically smaller perigee boosts and deboosts which increase only slowly with service altitude, plus a tether mass that increases with the square of the difference between the service altitude and 100 nm.

The best operating strategy probably is along the following lines. For concreteness, it assumes payload delivery from Vandenburg to a 300 nm circular sun-synchronous orbit, using a 16 nm swinging tether weighing about 700 lbs.

1. Launch the shuttle into a 30 x 286 nm direct-inject trajectory.
2. Raise the perigee to put the orbiter in a 115 x 286 nm orbit.
3. Do other mission tasks while in this 115 x 286 orbit.

4. Deploy the tether so it will swing through the vertical near apogee.
5. As the tether swings, boost the orbiter to keep perigee above 100 nm.
6. Release payload into 300 x 300 nm orbit and orbiter into 284 x 100 orbit.
7. Prepare orbiter for reentry, then deboost and reenter.

Compared to operations with OMS kits, this operation allows over a 50% increase in payload (from 19,000 lbs to 30,000 lbs using consistent ground rules). This payload enhancement approaches that possible with optimized upper stages, but at much lower development and operational cost. (This is mainly because no upper stage guidance or attitude control systems are needed for tether operations.)

The choice of a 115 nm perigee plus partial reboost during the tether swing is based on the following logic. At this perigee, the OMS usage required to reboost the orbiter during step 5 is the same as the additional deboost needed if the tether breaks. Higher perigees increase OMS requirements for emergency deboost, while lower perigees increase drag and the required tether mass, without reducing total OMS use in steps 2 and 5.

There are many unanswered questions regarding safety, compatibility with orbiter constraints, apsidal positions, practical limits on service altitude, and details of the deployer design and mounting concepts. However, due to the large benefits that this proposed application may provide, research on these questions should receive a high priority.

Shuttle-Based Tether for Deploying Upper Stages (Figs. 4 and 5)

This application is very similar to application 1. The main difference is that the payload/rocket combination is best released when the orbiter is near perigee, to minimize the "gravity losses" associated with the upper stage burn. Savings may generally be much smaller than with 1 because here the tether just shrinks the required upper stage rather than eliminating the need for one.

- **BENEFITS:**
  - **INCREASED PAYLOAD DELIVERY**
  - **LOWER PROPELLANT REQUIREMENTS**
- **PRACTICALITY: HIGH**
- **ISSUE:**
  - **SHUTTLE ORBIT ENERGY AFTER PAYLOAD RELEASE TO BE ABOVE ENTRY CONDITIONS**
  - **SPACE IN CARGO BAY TO HOUSE TETHER**

Figure 4. Shuttle-Based Tether for Upper Stage Deployment to Higher Energy Orbits

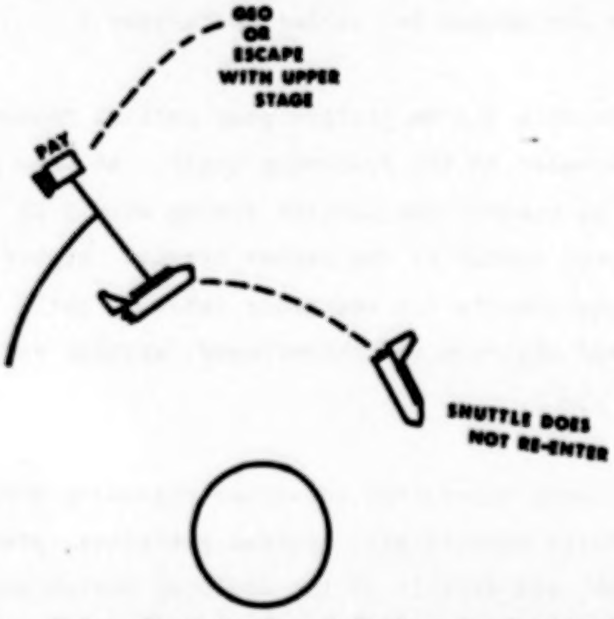


Figure 5. Using Shuttle-Based Tether to Assist Launch of Upper Stage for GEO or Interplanetary Orbits

The exact level of benefits provided by the tether depends on many details of the mission that will merely be mentioned here. First, the orbiter apogee before the operation may or may not be required by other payloads, and the apogee drop caused by the tether may or may not require makeup. If the upper stage comes in a fixed size that is slightly too small, or if the payload plus required stage weight exceeds the structural limits of the orbiter, a tether operation or some other performance-enhancement may be required.

The same questions asked in 1 apply here as well. In addition, spin stabilization before deployment is probably impractical, so other methods of upper stage alignment and stabilization need to be considered.

Overall, this application may make sense as a minor variation and extension of application 1, but is probably not worth pursuing independently of 1.

Downward Release of External Tank from Shuttle Orbit (Figs. 6 and 7)

This application is an "upside down" version of application 1, using the ET as "payload." The major effects are to initiate a controlled reentry of the ET and to boost the orbiter perigee; both of these effects are beneficial.

- BENEFITS: SAVES OMS PROPELLANT, INCREASES PAYLOAD, ALLOWS CONTROLLED DISPOSAL OF ET
- PRACTICALITY: MEDIUM
- COST BENEFITS: ?
- OPERATIONAL REQUIREMENTS: ATTACHING ET TO TETHER FROM ORBITER, IMPACT ON ORBITER ALTITUDE CONTROL

Figure 6. Downward Release of ET From Shuttle Orbit

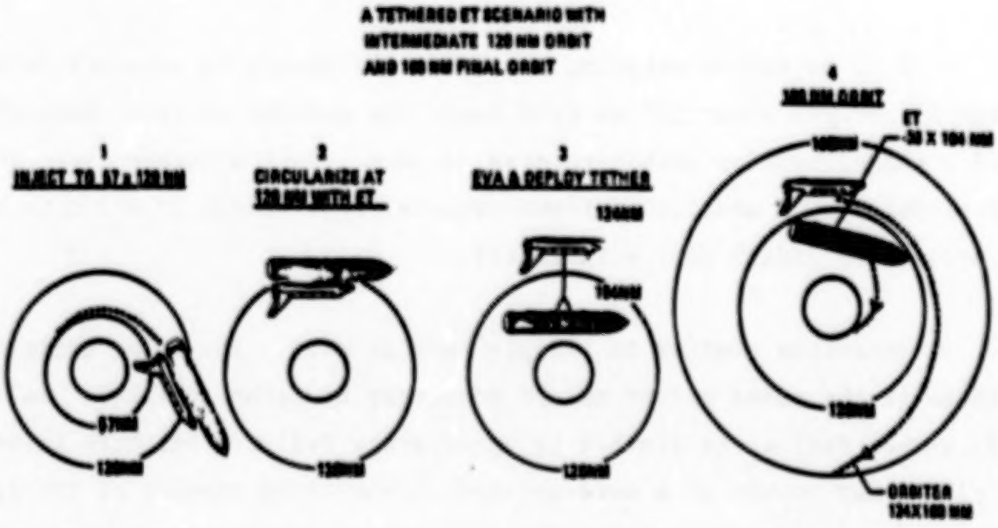

A TETHERED ET SCENARIO WITH
INTERMEDIATE 120 NM ORBIT
AND 100 NM FINAL ORBIT
1
INJECT TO 57 x 120 NM
57NM
120NM
2
CIRCULARIZE AT 120 NM WITH ET
120NM
3
EVA & DEPLOY TETHER
124NM
104NM
120NM
4
100 NM ORBIT
100NM
ET ~30 X 104 NM
120NM
ORBITER 124X100 NM

Figure 7. Typical Mission Scenario

The ET is currently disposed of while the orbiter is on its way to orbit. This constrains the orbiter to launch trajectories from which suitable disposal sites can be reached during the first orbit. In particular, current operations preclude service to inclinations between 57° and 70° from either KSC or VAFB, due to lack of suitable ET disposal sites.

Taking the ET into orbit before disposing of it allows the shuttle to wait until the earth rotates underneath the orbital track and provides a safe disposal site. For some cases already investigated, there are apparently many suitable opportunities during each day.

Delayed ET disposal also makes possible the following operations:

(a) Using an Aft Cargo Carrier to nearly double the useful payload volume

(b) Carrying extra supplies for long missions in the ET intertank

(c) Using ET pressurization gases in a small rocket to boost the shuttle

(d) Recovering residual ET liquids for other uses, particularly to allow (e)

(e) Launching a Shuttle-Centaur dry, for safety in case of mission abort.

A 12 nm tether weighing about 700 lbs should be adequate to reduce the ET perigee about 120 nm (and boost the orbiter perigee about 40 nm), if a wide-libration tether release is used. Such a tether might be deployed from a modified Get-Away-Special-type bridge in order to use payload bay length most efficiently.

Questions similar to 1 apply here as well. The major additional issue is the added safety hazard presented by tether failure. In 1 and 2, tether failure is similar to upper stage failure; but here tether failure may result in a more-or-less uncontrolled reentry of the largest object ever put into orbit. Thorough safety analyses must be done, and backup ways to adjust the ET impact point (on-board or remotely) must be investigated.

A surprising aspect of tethered ET-disposal is that it makes sense to try even if a full rocket-deboost system must also be carried as a backup. This is because the tether may more than pay for itself just by boosting the orbiter. Two disposal systems may also be more reliable than either one alone.

One possible development strategy is to start out with a tether system plus a rocket backup that is itself fully redundant. Then as experience is gained, it may be possible to substitute a smaller backup, with lower Delta-V and less redundancy. Eventually the on-board backup-system might be entirely eliminated, at least on missions where added lift capacity is needed.

Space Station Altitude Reboost and Shuttle Deboost with Tether (Figs. 8 and 9)

This is the first of three tether applications that use a space station-based tether deployer. Space station basing relaxes constraints on retrieval time. It also allows more ambitious tether facilities since the tether system need only be launched once, rather than every mission it is to be used.

The application considered here reduces the drag-makeup requirements of a space station by "scavenging" momentum from an orbiter that is about to leave the station to reenter. An early version might attach the tether to a bridge in the payload bay, and use a tether long enough to drop the orbiter perigee to about 100 nm. This leaves the orbiter in orbit after release, in case the initial attempts to close the payload doors are unsuccessful.

- BENEFITS: STATION AND SHUTTLE PROPELLANT SAVINGS AND REDUCED HEAT LOAD ON ORBITER AS A RESULT OF A MORE GENTLE REENTRY
- PRACTICALITY: HIGH
- COST BENEFIT: UNKNOWN
- OPERATIONAL REQUIREMENTS: TETHER SECURED TO SPACE STATION

Figure 8. Space Station Altitude Reboost/Shuttle Deboost with Tether

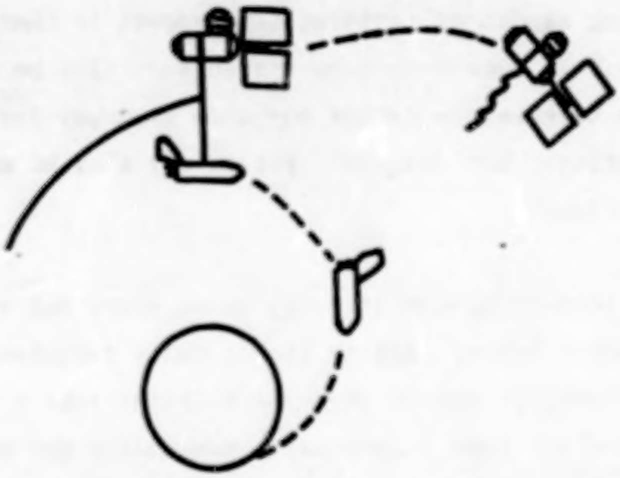


Figure 9. Reboosting Space Station by Lowering Shuttle When Ready for Reentry

Releasing a 180,000 lb orbiter into a 200 x 100 nm orbit from a station at 215 nm provides enough momentum to displace space station makeup burns of about 4200 lbs of OMS propellants (or 2900 lbs of cryos) on each mission. It also reduces orbiter deboost OMS-use by about 3700 lbs, but that must be kept available as an OMS reserve, to deboost the orbiter in case the tether breaks.

The next version might be to provide the orbiter with a tether-attachment point outside the payload bay. The front RCS module has been designed for easy removal, appears to have adequate strength, and might be modified to incorporate a flush or recessed tether attachment. This would allow use of a tether twice as long that actually initiates orbiter reentry. Such a tether could transfer twice as much momentum, and hence could save 8400 lbs of storables or 5800 lbs of cryos each time it is used. (This assumes the space station is kept in a low enough orbit to need that much boosting.)

A backup-means of deboosting the orbiter in case the tether breaks could allow the orbiter-deboost reserve to be offloaded for use on the station. One such backup would be to add a thruster package to the tether tip that attaches to the orbiter. If the tether breaks, this thruster would remain attached to the orbiter. It could then deboost the orbiter and be released and discarded. In normal operations, the thruster would not be used, and would be retrieved with the tether. This concept or a functional equivalent could free 7000 lbs of OMS fuel each mission for on-orbit use, in addition to the 8400 lbs of OMS fuel (or 5800 lbs of cryos) saved by the tethered station reboost itself.

The major orbiter-related issues appear to be the practicality of tether attachment points outside the orbiter payload bay, a reliable backup system to deboost the orbiter, and procedures for on-orbit transfer of OMS propellants.

In addition, the operations proposed here and in 5 and 6 impose three real constraints on space station design and operations. The first is that the station with all attached hardware must be able to withstand tether loads of 7000 lbs or more. The second is that the space station must have adequate mass (perhaps using ETs) if ambitious tether operations are intended. The third constraint is that momentum transfer operations, unless carefully paired, cause large shifts in the station orbit. Compensating for these shifts by rescheduling drag-makeup may take some time. It should be possible for a station to co-orbit with other platforms most of the time, but the station will be away from those platforms for significant periods.

Shuttle Docking with Space Station Via Tether (Figs. 10 and 11)

This operation is in essence a "time-reversal" of application 4; the orbiter docks with a tether deployed down from a space station and "borrows" momentum from the station during the mission. Major propellant savings only occur if the station has excess momentum from energetic tethered-deboosts of orbiters and ETs, or uses electrodynamic tethers or other electric thrusters.

- BENEFITS:
  - SHUTTLE PROPELLANT SAVINGS
  - EXTENDED PAYLOAD
  - SAFETY DUE TO REMOTE DOCKING
  - EASIER PROPELLANT TRANSFER
- PRACTICALITY: MEDIUM
- OPERATIONAL REQUIREMENTS: PRECISE RENDEZVOUS MAY REQUIRE "SMART" HOOK

Figure 10. Shuttle Dock to Space Station Tether

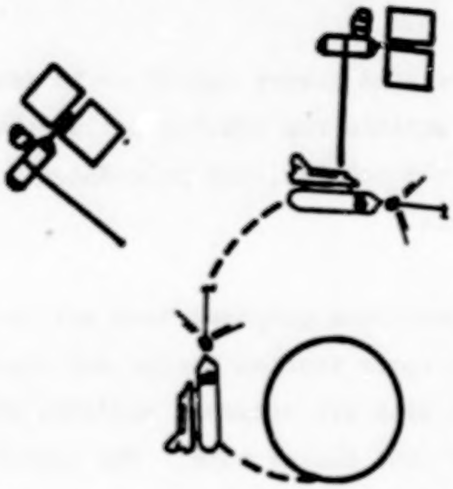


Figure 11. Docking Shuttle to Long Tether Lowered from Space Station--Enhances Payload and OMS to Station

In this case, the savings scale with tether length and are about 350 lbs per nm of tether for hanging-capture operations and up to 620 lbs per nm for swinging captures. If the ET is to be brought to the station for propellant scavenging or use, the savings are about 30% larger.

Three tether lengths are discussed below. Each causes new effects that increase both the operation's benefits and its difficulty. Each also serves as a subscale indication of the practicality of the next longer tether.

Tethers on the order of 1 nm long can save only small amounts of fuel. However, they may enhance space station safety, reduce contamination near the station, and reduce the effects of docking transients on flexible attachments. The tether might later be retracted to facilitate crew and cargo changeout and fuel transfer, or appropriate facilities might be built into the tether tip.

Tethers about 20 nm long hanging from a station at 215 nm (11 nm long if swinging) eliminate the shuttle circularization burn, since direct inject trajectories on the order of 57 x 200 nm result in shuttle apogee altitudes and velocities that match the tether tip. Tether loads after docking are several tons. The space station must be at least as massive as the shuttle in order to keep the perigee of the combined system high enough.

For tethers up to about 20 nm long, rendezvous windows may be extended as much as desired by using the orbiter's RCS/OMS thrusters to "hover" near the tether tip. It takes 5-10 minutes of such hovering to waste the amount of propellant that can be saved by a tether docking. If tethered docking in such a period seems unlikely, the shuttle can burn OMS fuel intended for transfer to the station, to boost to a conventional rendezvous and docking.

Tethers up to 150 nm long seem possible, but hovering or carrying enough OMS fuel to switch to conventional rendezvous are then impossible. In addition, for such long tethers swinging tether operations should be used to minimize the amount of time that the lower end of the tether is at low altitudes (and cause high drag). The launch trajectory must then permit a safe abort if tethered docking is unsuccessful. If this is acceptable, then launch Delta-Vs can be cut by up to 4000 ft/sec. This can more than double the useful payloads, but requires very massive space stations with masses on the order of 25 times the mass of the captured launch vehicle.

The possible payoffs of such operations range from large to enormous: up to 9000 lbs OMS fuel for 11-20 nm tethers, or over 90,000 lbs extra cryogens if swinging 150 nm tethers prove practical. The problems are also very large. They include precision rendezvous (perhaps using GPS); prompt docking (perhaps aided by a maneuvering tether tip); large loads (perhaps handled through a modified ET nosecone/docking probe, to keep the tether away from the orbiter); and large electric thrusters (perhaps using electrodynamic tether effects).

Tethered Boosting of Payloads from Space Station, With High I_{sp} Makeup (Figs. 12 and 13)

This application is a space station-based version of application 2. If lost momentum is made up conventionally, the benefits are limited, but--as in 5-- radical payload increases are possible if high-I_{sp} thrusters are used.

- BENFITS: LOWER PROPULSION REQUIREMENTS FOR SPACE STATION AND PAYLOAD (SYSTEM)
- PRACTICALITY: MEDIUM
- ISSUES:
  - SPACE STATION CHANGING ORBIT
  - INCREASED STATION POWER REQUIREMENTS

Figure 12. Space Station Based Tether to Assist GEO or Deep Space Launch with High I_{sp} Momentum Accumulator on Station

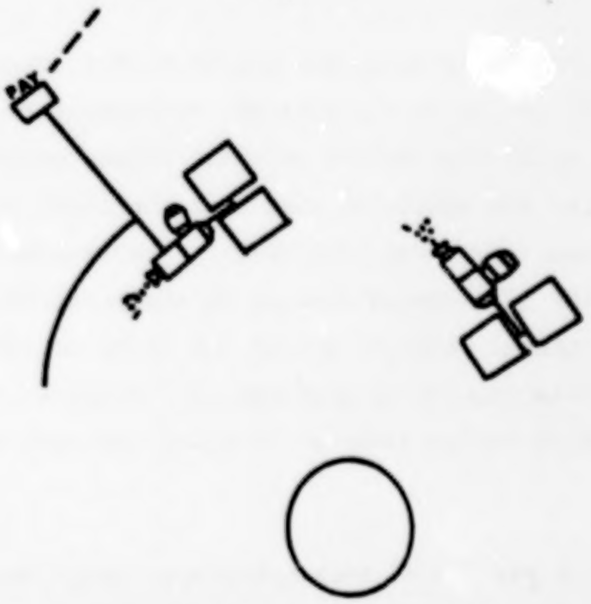


Figure 13. Using Station-Based Tether to Assist GEO and Deep Space Launch, Plus Electric Propulsion to Restore Orbit

The net effect of tethered boost and low-thrust, high I_{sp} makeup of lost momentum is to combine the low overhead mass and transfer times characteristic of chemical rockets, with the low propellant consumption of high-I_{sp} thrusters. This "best of both" combination provides an ideal application for electric thrust devices.

There are several unobvious benefits as well. First, the electric power system remains safely below the damaging Van Allen belts. Second, "off-peak power" can be used to reboost the station; this smooths power demands on the space station and reduces storage requirements. Third, the electrical power system and the thrust device are always accessible for maintenance or repair, since they are kept on the space station itself. And fourth, magnetic field strengths and electron densities are greater in LEO than at higher altitudes, so space station-based electrodynamic tethers may be practical for momentum makeup. This might totally eliminate any need for momentum makeup propellants.

Tethers based on a space station may be used many times, and hence can "pay for themselves" over many uses. Multiple uses can justify very ambitious tether facilities, capable of adding 4000 ft/sec or more to payloads. The tethers for such operations are more passive than the payload itself, and must be tapered for greatest mass-effectiveness. The use of very costly super-strength materials near the tip may be justified, since that allows the whole tether to be lightened.

Surprisingly, safety margins for this application can be lower than for other applications. This is because tether failure merely lofts the payload and tether into a low-drag orbit, from which they can be recovered by an OTV. A low safety margin allows a given tether mass to provide larger boosts, and this can more than offset the propellants wasted after an occasional tether break.

The major problems with this application seem to be limits on out-of-plane Delta-Vs, design of OTVs for compatibility with tether operations, transient effects on the space station orbit, loads imposed on the payload before release (up to 0.4 gee for a 4000 ft/sec tether Delta-V), and the practicality of large electric thrust devices and their required power supplies.

Applications 4-6 have been discussed separately, but they should all be able to use the same deployer hardware. This should increase the cost-effectiveness of these three applications.

Using Tethers to Boost Payloads and Deboost Spent Rocket Stages (Figs. 14 and 15)

This is the only tethered momentum transfer application discussed which is based neither on the shuttle nor on a space station. It is based instead on upper stage vehicles.

- BENEFITS:
  - ENHANCED PAYLOAD DELIVERY
  - PROMPT, CONTROLLED REENTRY OF SPENT STAGES OR DEBOOST OF REUSABLE OTVs
- PRACTICALITY: MEDIUM
- ISSUES:
  - TETHER SYSTEM PLACEMENT
  - ENTRY OF TETHER

Figure 14. Tethers Which Use Discarded Stages to Boost Payloads

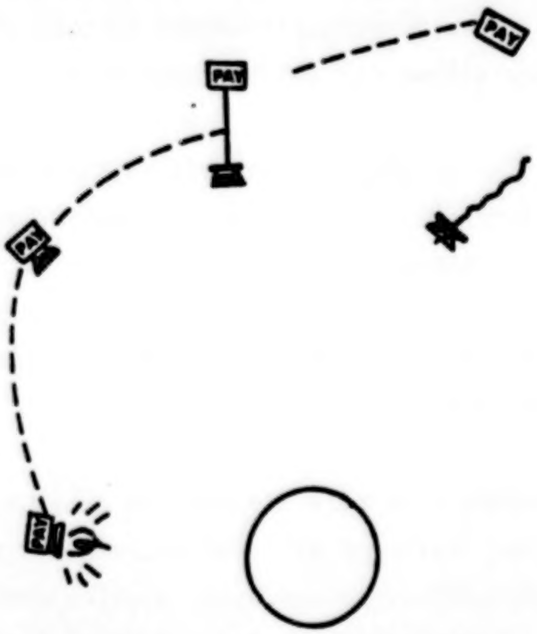


Figure 15. Using Tethers to Discard First Stages or Apogee Motors and Get Some Boost

The purpose is to transfer some of the momentum invested in a spent stage to its payload. Since this is done only once for each boost operation, the tether must fully "pay its way" each time it is used. Hence, this operation is limited to relatively modest Delta-Vs (on the order of 300 ft/sec). This in turn should allow payload increases of a few percent.

If the stage is expendable, then the tether pays for itself primarily by boosting the payload, and only to a minimal extent by causing a prompt reentry of the spent stage.

If the stage is reusable, tethered deboost may have significant value, since it can reduce the propellant required to return the stage to the space station that services it. Deploying a tether may itself be valuable, if the tether has an aeromaneuvering device at its end, or is a bare conductor that can create enough electrodynamic drag to complete the deboost. (These two concepts are covered in applications 9 and 10.)

Tether release might be done near either perigee or apogee. Release near perigee will further raise the apogee of the payload while reducing the apogee of the stage. Release at apogee tends to help circularize the payload's orbit while dropping the perigee of the spent stage; this requires a far longer but thinner tether for the same Delta-Vs as a release at perigee.

The major issues with this application seem to be the methods for storing and deploying the tether, its behavior during deployment in a transfer orbit which is typically very eccentric, and the amount of extra instrumentation and avionics required specifically for the tether operation.

The small benefits provided by this application, plus the cost of instrumentation and avionics, will probably limit this concept to use with advanced reusable OTVs, where the tether serves several purposes and the system costs are amortized over many missions. Experience with applications 1-6 could indicate whether this longer-term application is worth pursuing.

Modification of Orbital Energy and Eccentricity by Control of Tether Length (Figs. 16 and 17)

In the inhomogeneous gravity field, the net gravity force on the extended body does not coincide with the gravity force that would act on the total force at its center of mass, but depends on the configuration. Thus, if internal mechanical energy is used (or absorbed) to force appropriate modifications of this configuration, the net force will change, and the motion of the center of mass can be affected without mass expulsion. The net torque about the Earth's center remains zero, however, so no effect on the overall angular momentum will occur.

- BENEFITS: CHANGING ORBIT ECCENTRICITY WITHOUT EXPULSION OF MASS
- PRACTICALITY: UNKNOWN
- ISSUES: PRINCIPLE ESTABLISHED BUT APPLICATION REQUIRES FURTHER STUDY

Figure 16. Modifying Orbital Energy and Eccentricity by Angular Momentum Pumping

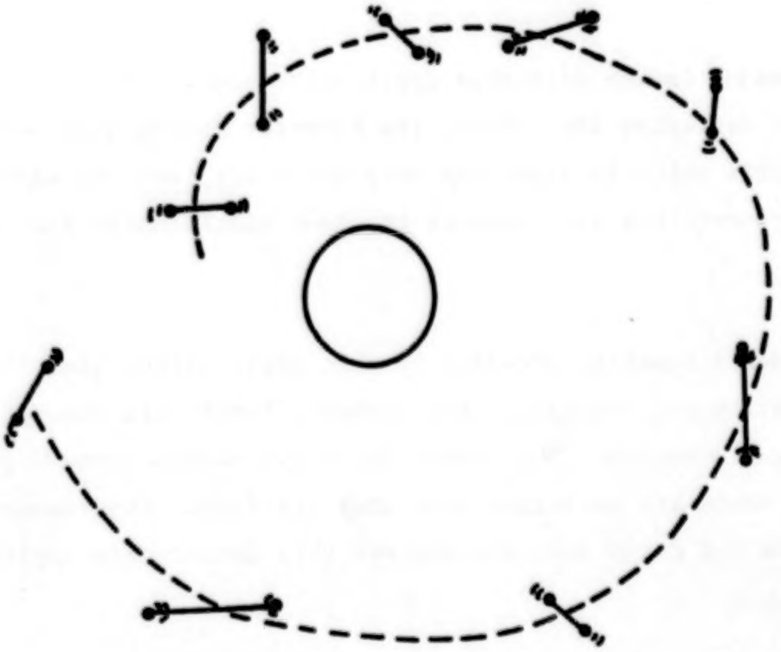
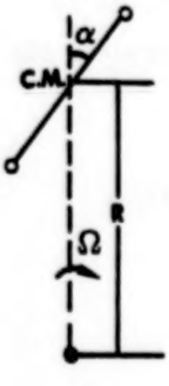


Figure 17. Modifying Orbital Energy and Eccentricity by Geometry Variations

Let Omega be the angular velocity or orbital motion of the c.m. in an orbit of radius R, I the moment of inertia in libration (by angle Alpha) and M the total mass. Then $L = M\ \text{Omega}^2\ R + I\ (\text{Omega} + \text{Alpha})$ remains constant. Suppose Alpha > 0 (forward libration); then Omega must be reduced relative to its value without libration. The reverse happens when Alpha < 0, and thus any in-plane libration implies simultaneous oscillations of the centrifugal force on the body. At fixed geometry, these oscillations are at some frequency different than Omega; for a long dumbbell, the frequency is 3 Omega. If we can manipulate the inertia I such that we excite a parametric oscillation of the dumbbell at precisely Omega, then the excess or defect of centrifugal force will always occur at the same point in the orbit, and the effect will accumulate, leading to a variation of eccentricity e with time. The energy will then also vary, since $E = M\ \text{micron}^2/2L^2\ (1 - e^2)$. For near-circular orbits, $e \ll 0$ and the variation of energy is small compared to that of eccentricity, but at larger eccentricities, substantial energy changes may occur.

For small amplitudes, the libration equation is

$$\frac{d}{dt}\left(I\ \frac{d\ \text{Alpha}}{dt}\right) = -3I\ \text{Alpha} \qquad \left(I = \frac{m1m2}{m1+m2}L^2\right)$$



If we force L to vary according to either $L = L_{max}$ cos Omega t or $L = L_{max}$ cos Omega t , then the solution for Alpha is Alpha = Alpha_0 sin Omega t, a finite amplitude libration at orbital frequency. This introduces a resonant forcing into the small-disturbance equations of the c.m. orbital motion, and in agreement with the preceding physical discussion, the result is a secular growth of the disturbance, and a long-term variation of the eccentricity. For an initially circular orbit one finds that both the apogee and perigee vary (in opposite directions) by the same amount per turn:

$$\text{Delta } R = \frac{3\ \text{Pi}}{2}\,\text{Alpha}_0\,\frac{I_{max}}{MR}$$

For equal masses, separated by a 100 km tether in LEO, and for amplitude $\text{Alpha}_0 = 1/4$ rad, this amounts to about 0.9 km per orbit. The maximum relative velocity of the end masses is about 100 m/sec. As discussed, the semi-major axis, hence the energy, does not change to first order for small eccentricities.

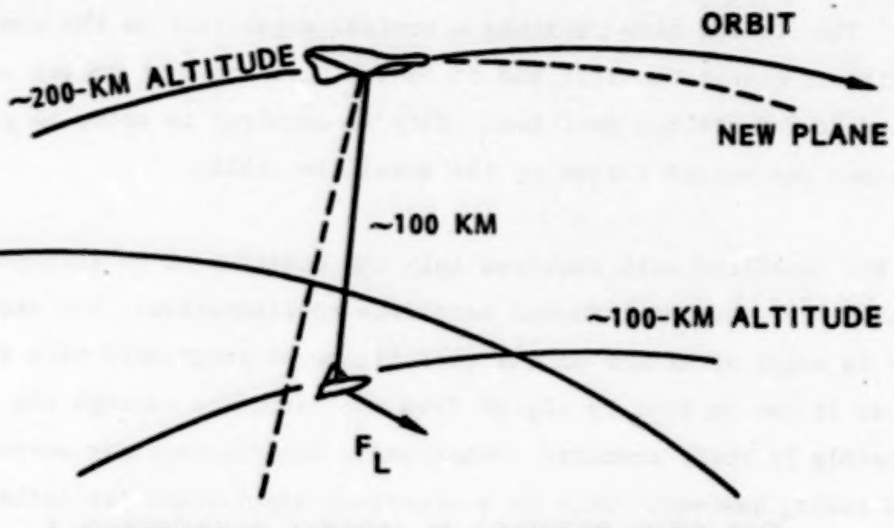
This effect could probably be most useful in circularizing highly elliptic orbits by absorption of mechanical energy (but without propellant expulsion), or vice versa, to achieve near-escape from moderately high initially circular orbits, this time by expenditure of energy on board. It is probably premature to think of applications, however, until the fundamentals of the effect have been more thoroughly studied (i.e., are there more convenient, high amplitude, lower frequency "pumping" laws?). It is interesting, however, that we do have the actual possibility of using purely internal forces for orbit modification.

The Satellite Sail (Figs. 18 and 19)

An aerodynamic surface is lowered from a satellite on a long tether into the upper atmosphere, where it is oriented to give a horizontal force on the satellite through the tether. This force is modulated as a function of the orbital position in order to process the orbit or to change its orbital plane.

- BENEFITS: INCLINATION CHANGE WITH REDUCED PROPELLANT, ECCENTRICITY CHANGE. PROCESS POLAR ORBITS
- PRACTICALITY: HIGH
- ISSUES:
  - TETHER AND SAIL MATERIALS TO WITHSTAND HEATING LOADS
  - VALUE OF L/D
  - TETHER DRAG
  - SLOW MANEUVER IMPLEMENTATION

Figure 18. Aerodynamic Sails for Plane Changes in LEO



A HYPERSONIC AIRFOIL IS LOWERED INTO THE UPPER ATMOSPHERE TO CHANGE THE ORBITAL PLANE

Figure 19. Satellite Sail

The satellite sail could change the orbital plane of the space shuttle by 0.5-1.5 degrees per day with a 100-square meter airfoil lowered to 90 km altitude. The losses associated with the drag of the tether and the airfoil are much less than the corresponding losses due to changing the orbital plane by direct rocket thrust or by dipping the shuttle into the upper atmosphere and performing an aerodynamic maneuver. The sail would allow the shuttle to deploy a satellite into one orbital inclination, change its orbit, then deploy or retrieve a satellite in a second orbital inclination before returning to base. Alternately, the sail could be deployed on the satellite itself, allowing it to change its plane from the nominal 28.5° orbit of the shuttle to its desired orbital plane. This could be done at leisure, taking days or weeks and requiring very little energy. This technique would free the shuttle, with its greater mass, from having to change its plane.

The satellite sail would require the use of high-temperature tether materials and high-temperature materials for thermal protection of the aerodynamic surface. The tether material also needs to have a high residual strength at the elevated temperature. The greater the heat resistance of the tether and sail materials, the lower the altitude

the sail could be deployed and the greater the rate of change of orbital plane. The concept also requires a control capability on the shuttle or satellite to deploy the sail and to control its angle of attack as a function of the orbital position. This is required in order to provide the proper precession torque on the satellite orbit.

The satellite sail requires only the addition of an aerodynamic surface to the current tethered satellite configuration. The required change in angle of attack of the airfoil can be programmed into the body, or it can be sent by signal from the satellite through the tether, or possibly by radio command. Ionospheric interference may prevent the use of radio, however. This is a near-term application for tethers.

The satellite sail could free the shuttle from the problem of deploying or servicing satellites in many orbital planes. If used on the satellites themselves, the shuttle could perhaps be launched into just two orbits—28.5° from KSC and 90° from VAFB. All the plane change necessary for individual spacecraft could be applied through sails deployed from the spacecraft themselves. This could include the orbital change required for a geostationary satellite deployed from the 28.5° orbit. A 10-square-meter sail would suffice for the heavier satellites, and it could be discarded when the plane change was completed.

Jerome Pearson, The Satellite Sail, presented at the AFIT/AIAA Minisymposium, March 1983.

Electrodynamic Braking of Tethered Satellites

To make continued close observations by explanatory probe, the probes should be captured in a low altitude orbit. For planets with an ionosphere and magnetosphere, electrodynamic braking can provide a soft deceleration mechanism for capture, which would eliminate the need for retro-rocket propulsion. For satellites in earth orbit, the same electrodynamic braking could be used to deorbit.

The satellite is divided into two approximately equal parts by payout of an electrodynamic tether in a gravity gradient stabilized configuration. A retarding force is exerted on the tether due to the induced current. The power in the current generated in the tether is dissipated in the tether itself or in an auxilliary load, where it is radiated away. As a result, the orbital velocity is reduced.

The maximum power which can be from the tether is of the order of RhoTau F_{GG} Upsilon where the gravity gradient force is F_{GG}, and Upsilon is the orbital velocity. The characteristic time Tau for dissipating the orbital kinetic energy E_k is then

$$\text{Tau} \sim \frac{E_k}{\text{Rho}} \sim \frac{M\ \text{Upsilon}^2}{F_{GG}\ \text{Upsilon}} = \frac{\text{Upsilon}}{3\ \text{Omega}^2\ L}$$

The number of revolutions about the planet to reduce the energy by a major fraction is

$$NR = \frac{\text{Upsilon Tau}}{2\ \text{Pi}\ R} \sim \frac{\text{Upsilon}^2}{6\ \text{Pi}\ R\ \text{Omega}^2\ L} = \frac{1}{6\ \text{Pi}}\ \frac{R}{L}$$

Tethers should be shorter than the characteristic length Lambda = 1/Omega S/3 Rho which is about 300 km for strong materials in LEO. We find for near earth orbits, $N_R \sim 1.5$ revolutions. In general, for Jupiter, Upsilon_e is about 4 times earth escape velocity and N_R is about 10 revolutions.

$$N_R \sim R\ \text{Omega}/\ \ S/3\ \text{Rho} \sim \text{Upsilon}_e$$

where F_{GG} = gravity gradient force
Upsilon = orbital velocity; Upsilon_e escape velocity
Omega = orbital angular velocity
R = planetary radius
L = tether length
S = working stressed tether (10^{10} dynes/cm^2)
Rho = tether material density (2 g/cm^3).

Planetary Tethers (Figs. 20 and 21)

A long tether is lowered from a satellite in orbit about the moon, for example, and tethers the satellite just beyond the Lagrangian unstable balance point L1 or L2. The satellite is then raised somewhat to just beyond the balance point and then moves on the tether like a spherical pendulum. Because of the lower gravitational field of the moon compared with the earth, such tethers could be done with existing high-strength materials.

- BENEFITS: CLOSE OBSERVATION OF BODIES, ENERGY MANAGEMENT
- PRACTICALITY: ??
- ISSUES: COSTS, OPERATIONS, CONSTRUCTION

Figure 20. Planetary Applications of Tethers

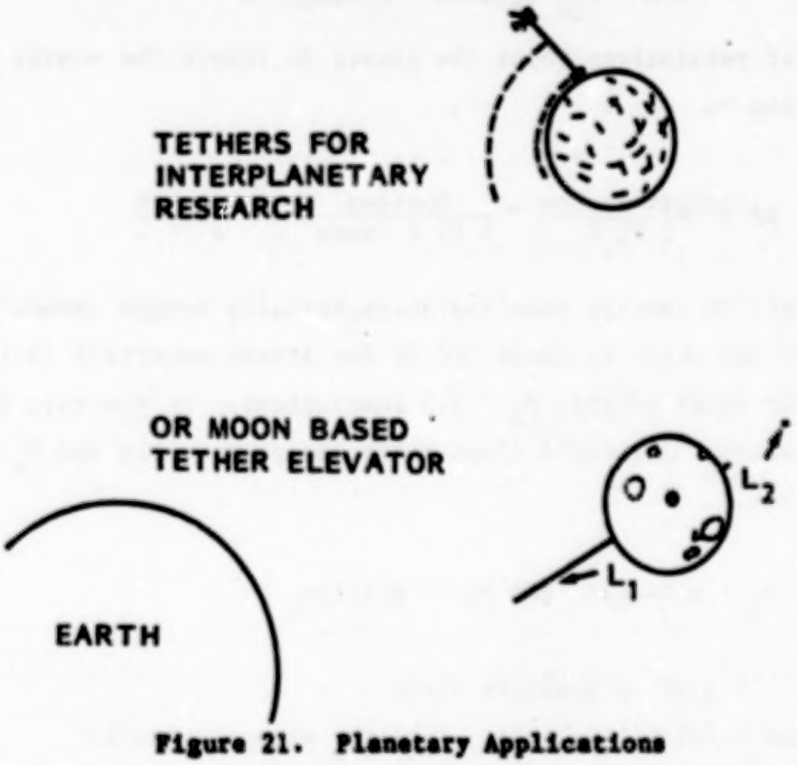

TETHERS FOR INTERPLANETARY RESEARCH
OR MOON BASED TETHER ELEVATOR
EARTH
L_2
L_1

Figure 21. Planetary Applications

The lunar tether could anchor a satellite just beyond L2 on the far side of the moon, 70,000 km from the lunar surface. From this vantage point, oscillating in a wide orbit that is a complicated Lissajous pattern behind the moon, it would be visible from the earth and the fair side of the moon simultaneously, and be able to provide continuous communication with any probe or installation on the far side of the moon. The lunar tether could also be emplaced on the near side of the moon, anchoring a mass past the L1 point, 66,000 km from the moon's surface. This installation could be used to bring up materials from the surface of the moon by simple mechanical means on the supporting tether. The energy requirement for this is just 0.7 kW-hr per kilogram. Once the material is brought past the L1 point, it can be released into a high earth orbit, where it could be used for construction of solar power satellites or could be used for the production of liquid oxygen rocket propellant for use in earth orbit. The installation on the near side of the moon could also be used to provide a means for soft lunar landings without the use of retrorockets by allowing payloads to move down the tether in a controlled fashion.

The planetary tether could make use of existing materials; current high-strength composite materials show the necessary strength-to-weight ratios. There would be the problem of long-term degradation of the materials strength due to exposure to vacuum and ultraviolet radiation. There are also the dynamic problems of extending the length of tethers far beyond the currently proposed 100 km. This would require the testing of the concept on a small-diameter, small payload mission before committing to full-scale construction. It would also, of course, imply the existence of an extensive lunar flight capability and support capability before the full-scale construction could begin.

There are some long-term materials problems that have not been addressed, and there are also some dynamics problems that have not been fully addressed analytically. The issues need to be examined critically before the project could be undertaken. This is a far-term project, because it requires an extensive lunar flight capability for its full utilization.

The lunar tether could provide long-term, continual communication with the lunar farside without the use of stationkeeping propellant. It could also provide the capability of bringing lunar materials into earth orbit for a very low cost. If the lunar L1 tether could be emplaced to raise lunar materials into earth orbit, it could be used in lieu of massive earth-orbit launches for orbital construction and propellant supply. Once the capability was in place, this would be a more efficient method of providing mass in earth orbit than lifting it from the earth's surface.

Jerome Pearson, "Anchored Lunar Satellites for Cis-Lunar Transportation and Communication," Journal of the Astronautical Sciences, Jan-Mar 1979.

III. RECOMMENDATIONS

Applications 1 through 7 (shuttle, external tank, and space station tethers) should be thoroughly studied as soon as possible to:

- Define the systems accurately enough to permit valid engineering and cost comparisons.
- Identify technological implications and any new technological developments required.

Application 8 (angular momentum pumping) should be investigated conceptually.

Applications 9 and 10 (aerodynamic sails and electrodynamic braking) represent tether interaction with the environment. Both have high promise and technological studies should be pursued.

Application 11 has not received much attention. Tethers may have utility in further planetary or lunar exploration. Planetary study groups should be encouraged to include studies of tethers in their future activities.

IV. PRESENTATIONS MADE TO THE PANEL

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PRESENTATION 1

THE ROCKET/SKYHOOK COMBINATION

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F. Burke Carley and Hans P. Moravec

Why You Should Read This Article

The task of delivering 50 million kilograms of payload to low Earth orbit would require almost 1700 launches of the Space Shuttle if done in a straightforward manner. Judicious use of a large satellite incorporating a high specific impulse engine and a long tapered Kevlar cable, itself transported to orbit in multiple shuttle flights, could cut the total number of launches, including the satellite construction phase, to about 300.

Dream On

A relatively new class of proposals for travel to and through space involves the idea of very long, very strong, tapered cables, spinning so that their tips move at or near orbital velocity. Although the concept promises to be one of the simplest and cheapest for massive orbital commuting in the long run—and could be used today for travel in space and on the Moon if there were call for it—present strength of materials limitations make the simplest variants of the idea infeasible for the most immediate need, namely transportation to and from Earth.

Two major types of Earth orbital cable (sometimes called skyhook) have been investigated in the literature. The simplest, but also largest, has a filament dropped to the surface from synchronous orbit, counterbalanced by one extending outwards. Anchored to the ground and kept taut by a ballast at the far end, this structure could be used as the backbone for an orbital elevator system (Figure 1). It has been rediscovered on at least three separate occasions (1) (4) (6) and is the central theme of two science fiction novels (3) (7). The second kind is newer, but has also been the subject of rediscovery

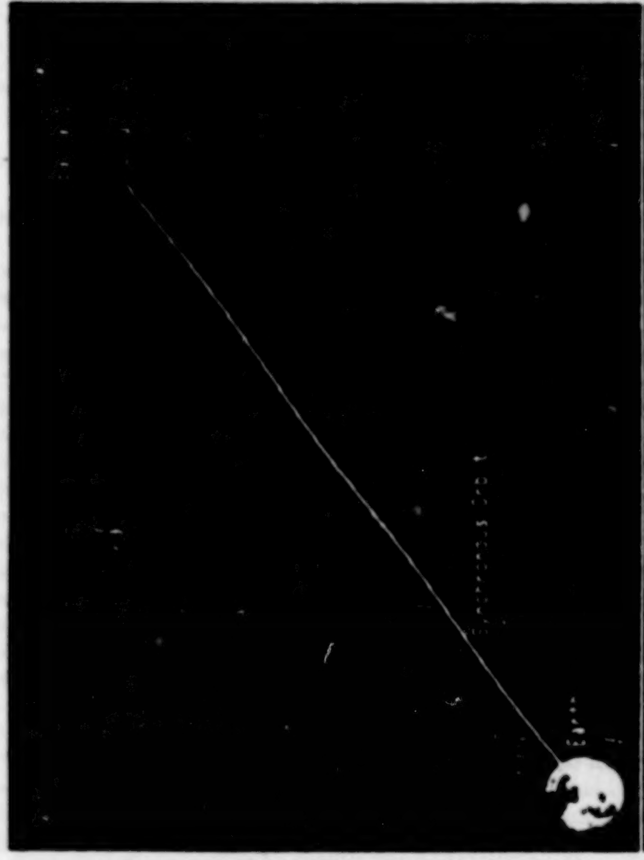

Figure 1: The Synchronous Skyhook (or beanstalk or orbital tower). This is the simplest and most elegant of all the cable-to-orbit schemes. It is also the largest, most demanding and most expensive. A 150,000 kilometer cable is grown upwards and downwards from synchronous orbit. When the lower end reaches the ground it is firmly anchored. A ballast which keeps the entire cable in tension (by virtue of centrifugal force produced by the Earth's rotation) is flown and attached to the far end. The cable can then be used to support climbing and descending payloads.

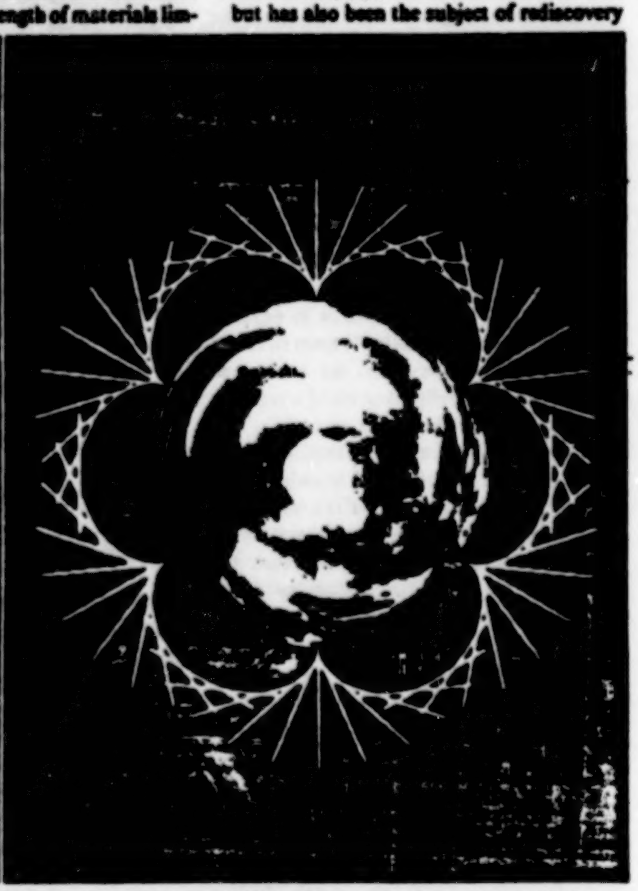

Figure 2: The Rolling Skyhook. This diagram shows the area swept out during one orbit. The cable length shown (about one third the Earth's diameter) is optional in the sense that this length minimizes the skyhook mass for a given lifting capacity. The skyhook touches down six times during each two hour orbit. Near the touchdowns the cable tip moves vertically, and the tip, with a constant upward acceleration of 1.4 g comes to a momentary stop. It could pick up payloads during these encounters, and release them a half rotation later with enough velocity to take them to the orbit of Saturn. Such launches subtract orbital momentum from the cable.

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(2) (5). It involves a much smaller cable in low orbit which rolls in its orbital plane and whose ends brush the Earth with the rotational motion cancelling the orbital motion at ground level. It is as if the cable were two spokes of a giant wheel that rolled along the ground (Figure 2). Payloads could be picked up on a spoke touchdown, and launched a half rotation later with greater than escape velocity. The momentum lost by the cable in this process could be returned slowly by high specific impulse engines at its center, or by capturing and landing payloads in a reverse of the launch process. With the latter approach the energy cost of orbital commuting becomes vanishingly small.

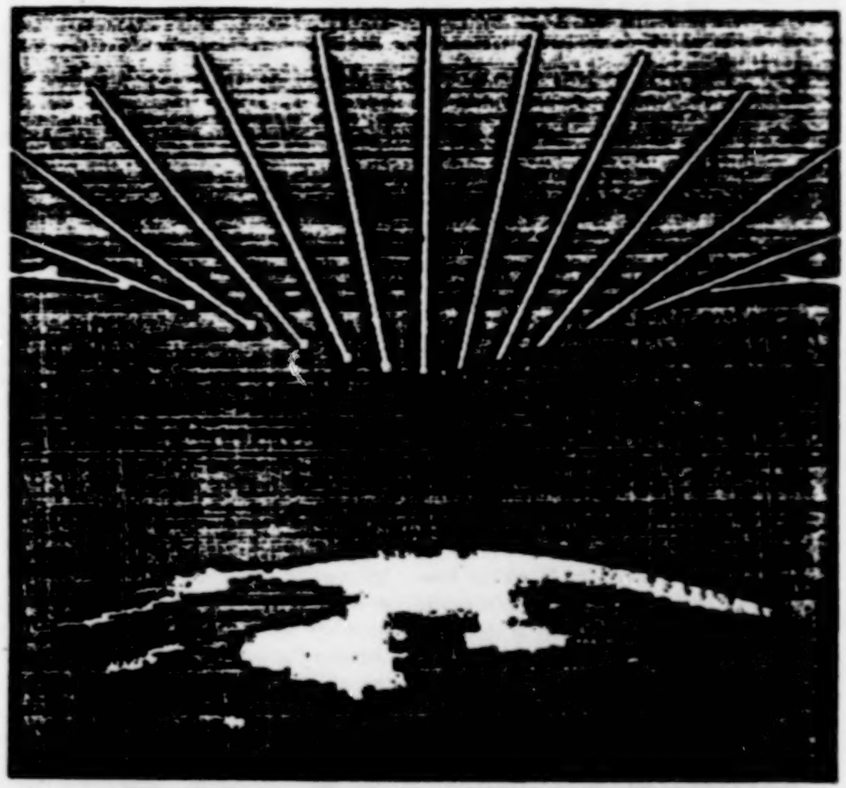

Figure 3: A Rocket/Skyhook Combination. A (relatively) short orbiting cable is spun moderately so that its tips move at about half orbital velocity. A (also relatively) small suborbital rocket able to achieve half orbital velocity delivers a payload to the skyhook tip, which then accelerates it to full orbital speed and beyond. This variant could be built today. The dotted path is the payload's trajectory.

Dupont Needs More Spinach

The problem with the above schemes is that the taper and mass required by the cables is exponential in the square of the weight/strength ratio of the cable material, and is astronomical if the material is too weak. The strongest commercially available material is Dupont's Kevlar synthetic fiber, which is five times stronger for its weight than steel. A synchronous skyhook of Kevlar would weigh 10^{13} as much as it could support at one time, while an optimally sized Kevlar rolling cable would be 10^{7} times as massive as its payload. A material only five times as strong as Kevlar would bring these numbers into the range of the feasible. With such a material the synchronous cable would mass 10,000 times as much as its payload and the rolling cable only 100 times its lifting capacity. Since the cables can move such payloads repeatedly, they could ultimately transport many times their own mass.

Although five times the strength of Kevlar is well within the theoretical bounds for normal matter, and strengths of this magnitude have been observed in the laboratory in small samples of several substances, the timescale for commercial availability of such strength in bulk materials is uncertain.

Half A Skyhook Is Better Than None

For a given material, the required mass of a spinning cable is exponential in the square of the desired velocity of the cable tips. Similarly the mass ratio of a rocket is exponential in the velocity it must achieve. These facts suggested to us that a combination of rocket and skyhook, each providing about half the velocity needed for Earth orbit, might be superior to either alone. A spinning cable in low Earth orbit would catch a rocket-accelerated payload moving at about half orbital velocity and accelerate it to full orbit, in a lower energy version of the rolling skyhook maneuver (Figure 3).

Besides giving an overall mass advantage, combining a rocket with a skyhook makes it practical to use weaker materials in the skyhook. Our analysis of a number of situations using the space shuttle as the rocket and Kevlar as the skyhook construction material lead us to the following encouraging results.

Encouraging Results

With the rocket/skyhook combination and large task of delivery to space can be accomplished with less material than with either method alone.

We chose to minimize the number of launches of the Space Shuttle to deliver 50 million kilograms to orbit. This task would require 1695 launches of the rocket alone.

Instead we imagine a cable grown upward from an initial orbital altitude of 185 km. As construction proceeds the shuttle docks with the lower end of the growing skyhook. As the skyhook lengthens, its center of mass moves into higher orbits, and its lower end moves more and more slowly with respect to the ground. The shuttle can thus arrive and dock at lower and lower velocity, with correspondingly greater payload per trip. The payloads would then be ferried up the cable, elevator style.

We also considered two similar schemes. In one a shorter cable in low orbit spins so that its lower tip moves at reduced velocity, in a small scale version of the rolling skyhook mentioned earlier. This variant results in the least number of necessary launches, but provides the least time and highest g forces for docking. The third possibility involves a cable that oscillates about ninety degrees from the vertical in each direction, under influence of the vertical gravity gradient. This "rocking" cable can transport payloads to orbit velocity without being climbed, and is intermediate in its properties between the vertical and spinning varieties.

The skyhook structure, whichever variety, incorporates a power plant and a propulsion system to boost the upper end of the growing skyhook into the correct orbit, and to replace orbital momentum transferred to the shuttle payloads on each docking. The power plant was assumed to have a power density of 10 kilograms per kilowatt and the propulsion system a thrifty specific impulse of 5000 seconds, about the numbers for solar electric ion engines suggested for comet missions.

The skyhook can be looked upon as an energy and momentum storage system by which an ion engine operating for long periods can accumulate its effect for the short,

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high intensity, spurts needed in an Earth launch.

Summary

The following table summarizes the results for a range of possibilities. The strength column gives the strength to weight ratio of potential materials, in units of "specific length," which is tensile strength divided by density times one gravity. Intuitively specific length is the length of material fashioned into a uniform rope that can just support itself when suspended from one end in a uniform 1 g field. Kevlar has a nominal specific length of 200 kilometers, but if the cable is built assuming this strength there would be no allowance for unexpected loads or for slight deterioration of the material. An assumed strength of 100 km lets the skyhook operate at a stress equal to half of Kevlar's strength, and 50 km would give us a very conservative safety factor of four. We have included an entry for 400 km to allow for near future advances in materials.

	Skyhook			
Type	Strength	Length	Payload	Total Launches
shuttle alone		0	1	1695
vertical	50km	1530 km	3.1	653
rolling	50 km	700 km	4.5	464
vertical	100 km	2300 km	4.2	510
rolling	100km	1010 km	6.5	336
vertical	200 km	3470 km	6.0	387
rolling	200 km	1500 km	10.5	233
vertical	400 km	5280 km	8.8	291
rolling	400 km	2190 km	18.3	160

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PRESENTATION 2

THE SATELLITE SAIL

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Abstract

It is proposed to suspend an airfoil from the Space Shuttle by a long tether into the upper atmosphere to provide a horizontal force on the Shuttle, thereby changing its orbital plane most efficiently. The airfoil would need high-temperature skin and tether, and remotely controlled flaps to adjust its angle of attack. The airfoil could also be used as a hypersonic facility to measure aerodynamic characteristics at extreme altitudes and velocities. This use would require a vertical lift force to counteract the drag force and prevent the Shuttle orbit from decaying too rapidly during the aerodynamic measurements.

I. Introduction

Since the first earth satellite was orbited in 1957, there has been an increasing use of many different kinds of satellites in earth orbit to perform a variety of tasks. For some of these tasks, such as worldwide communications, the satellite must be in an equatorial orbit with a period of one day, so as to appear fixed over a point on the equator. For other tasks, it is desirable to have the satellite in polar orbit, so as to pass over every part of the earth. For manned satellites and other uses, orbits of intermediate inclination to the equator are desired. For example, the orbit that requires minimum fuel to reach from a given launch point has an inclination equal to the latitude of the launch point. As a result, there are hundreds of satellites now in earth orbit, with inclinations to the equator ranging from zero to more than 90 degrees (retrograde).

With the advent of the re-usable Space Shuttle, it has become possible for one spacecraft to launch or retrieve many satellites on a single mission. This means that the shuttle must change its orbital inclination before each deployment or retrieval of a satellite, in order to match the satellite orbit. Unfortunately, changing the inclination of a spacecraft orbit is very expensive in energy. For example, the total velocity change required to launch a satellite into a minimum-energy orbit from Cape Caraveral is about 8 kilometers per second. For a polar orbit, the requirement is about 9 kilometers per second, because the additional velocity of the earth's rotation cannot be used.

However, to change the spacecraft orbital inclination from equatorial to polar once it is in orbit requires a total velocity change of 12 kilometers per second. This is such a severe requirement that it is easier to land and start all over again rather than change the velocity while the spacecraft is in orbit. Smaller orbital inclination changes can be done using much less velocity change, but it is still a very difficult operation with current rockets. No spacecraft has yet changed its orbital inclination by more than one or two degrees.

II. Shuttle Sail Concept

The purpose of this paper is to propose a new technique for satellite plane changing that is more efficient than rocket thrust or aerodynamic maneuvering.[1] The satellite sail is an airfoil suspended into the upper atmosphere on a long tether, allowing it to experience significant aerodynamic forces while the satellite is above any sensible atmospheric drag. The airfoil is oriented so as to provide a horizontal lift force on the satellite, thereby precessing its orbital plane to the desired new inclination. The device is called a satellite sail because it would function analogously to a sail on a watership; it would change the vessel's velocity by intercepting the relative wind.

An artist's concept of the satellite sail is shown in Figure 1. The satellite, shown here as the Space Shuttle, is in low orbit, about 200 km above the earth, and above the sensible atmosphere to the extent that aerodynamic drag is negligible. The airfoil is stored for launch in the Shuttle cargo bay and, once in orbit, is deployed downward from the satellite by the long tether and reel mechanism, and is stabilized by the gravity gradient. The Shuttle sail would be capable of multiple re-use; it is designed of high-temperature materials with no ablation during use. The tether itself could easily be replaced to prevent excessive abrasion by the reel mechanism.

Requirements

The Shuttle sail is dependent on two previous developments—the long-thethered satellite and the hypersonic airfoil. Plans have been developed by Colombo to tether subsatellites up to 110 km

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below the Space Shuttle for scientific measurements at an otherwise inaccessible altitude.[2] These long-tethered satellites would be stabilized vertically by the gravity gradient.[3] It has also been proposed that satellites be attached to the earth and moon by even longer tethers.[4] The dynamics of the tether and satellite motions have been investigated and Rupp has patented a mechanism for deploying and retrieving such a tether.[5, 6, 7] The conclusions of these and other technical studies is that tethered satellites with tether lengths of tens or hundreds of kilometers can be successfully deployed, stabilized by the gravity gradient, and retrieved.

The shuttle sail concept also draws upon the high-temperature, hypersonic design experience growing out of the Space Shuttle program and of research on the "synergetic" maneuver. An aerodynamic vehicle such as the Space Shuttle can use the atmosphere to change its orbital plane. Using rocket thrust to lower its orbit, the Shuttle could dip into the atmosphere, bank to provide a horizontal lift force, then use rocket thrust again to raise its orbit back to the former value, in the new plane. This maneuver is called the "synergetic" plane change, and it was developed by the United States Air Force in the 1960's during the Dynasoar program by London, and later optimized.[8, 9] These Air Force studies also developed designs for high lift/drag hypersonic airfoils, and the National Aeronautics and Space Administration has developed high-temperature insulation for the surfaces of re-entry vehicles.[10, 11] Combining these technologies has resulted in proven design techniques for hypersonic, high-temperature wing design.

Baseline Design

We will now examine in detail one point design for the satellite sail. The Space Shuttle operational characteristics and plane-changing requirements indicate the use of a typical, symmetric, highly sweptback hypersonic airfoil with added shuttle-tile thermal protection.[12] The thickness-chord and edge radius-chord ratios can be minimized because there is no need for significant internal volume or great stiffness.

The baseline design, shown in Figure 2, is a 100-square-meter airfoil of bolted, two-section construction, hinged to fold into the Shuttle cargo bay. The overall length is 27 meters, the maximum width is 5 m, and the maximum thickness is 15 cm. The airfoil has a 10-degree half-angle nose and a rectangular aft section. The construction is typical graphite/epoxy composite structure with central spar, edge tubes, and integral stiffeners. The laminated graphite/epoxy skin is in typical 0/45/90 ply orientation for highest isotropic strength. The entire surface of the airfoil, including the control surfaces, is coated with 2 cm of Space Shuttle silica tile heat insulation, type LRSI.[11] The airfoil is symmetric and is equipped with moveable aerodynamic control surfaces (double-acting flaps that can be moved to either side of the airfoil), and a typical S-band radio receiver and controller to accept the commands from the satellite. The satellite sail would require a controlled angle of attack so that the horizontal force could be adjusted as a function of the satellite orbital position. The tether length and airfoil angle of attack, and thus the airfoil position and aerodynamic forces, can be controlled remotely from the satellite by the reel mechanism and by signals from a radio transmitter, or by a pre-programmed controller inside the airfoil. The total mass of the sail, including the controls, electronics, and motors, is estimated to be 1500 kilograms. This sail, lowered to 93 km altitude, will precess the Shuttle orbit by 1.5 degrees per day. The parameters are summarized in Table 1.

Simplified Analysis

When two masses in orbit are connected by a tether, the tether experiences a tensile force aligned along the local vertical. This is the gravity gradient force. When the Shuttle sail is deployed on its tether, the total force on the airfoil is composed of the gravity gradient, the aerodynamic lift and drag, and the tether tension. For a nominal Shuttle orbit of 185 kilometers altitude and a nominal sail altitude of 93 km, the gravity gradient produces a downward gravitational force on the sail of 0.04 g, or 592 newtons force for the baseline design.

Using Newtonian momentum theory, in which the airstream velocity component normal to the airfoil is reduced to zero upon impact with the airfoil, the lift coefficient is found to be 0.05961 for an angle of attack of 10 degrees. With a dynamic pressure Q of 54.4 newtons per square meter at 93-km altitude and an area A of 100 square meters, the total lift force (oriented laterally to the direction of the Shuttle motion) is 329 newtons.

At an angle of attack of 10 degrees, the L/D is typically a maximum of about 3.2, including the effects of skin friction and profile drag as well as the drag due to lift.[12] However, the tether drag must be taken into account. Assuming a tether diameter of 1.72 mm and an atmospheric Q that decreases by a factor of two for each 4 km of altitude, the additional drag of the tether reduces the effective L/D from 3.2 to 3.0. To minimize the reduction in L/D due to tether drag, it might be possible to elongate the tetherline itself in the direction of motion, using a flattened profile.

With L/D of 3, the drag force is 110 N, including the tether drag. The tether tension from these three mutually orthogonal components is then 686 N. With a safety factor of two, the baseline design can be met by a wire of A-286 high-strength, high-temperature steel alloy with a diameter of 1.72 mm. The upper part of the tether wire is under less severe temperature constraints and could use type 302 stainless steel with a diameter of 1 mm. Only the lowest 20 km of the tether would need the high-temperature steel.[13] Other superalloys or nonmetallic tethers might also be used.

The precession rate Ω is given in terms of the satellite angular velocity ω, the torque L acting on the satellite, and the moment of inertia I of the satellite in its orbit by the equation

$$\Omega = L/I\omega \qquad (1)$$

The torque L is the vector product of $r \cos \theta \times f$ where $r \cos \theta$ is the projected radius vector moment arm and f is the lateral force acting on the vehicle. Since $f(\theta)$ is given by $f \cos \theta$, the equation for the torque is

$$L = r\, f \cos^2 \theta \tag{2}$$

The torque averaged over a half revolution is

$$L = r \cdot f \cdot \frac{2}{\pi} \int_{\theta = o}^{\pi/2} \cos^2 \theta \, d\theta = \frac{rf}{2} \tag{3}$$

The equation for the precession rate is then

$$\Omega = \frac{L}{I\omega} = \frac{rf/2}{mr^2 c\omega} = \frac{f}{2mr\omega} \tag{4}$$

In order to precess the plane of the satellite orbit, the lift vector must be varied from port to starboard and back once per orbital revolution. Note that the required change in tether angle, and therefore the lift force and the flap setting, is very slow; a complete cycle from positive to negative tether angle takes more than an hour. This means that relatively slow, low-force flap actuators may be used. To increase the orbital inclination, the tether angle must provide a northward force as the satellite crosses the equator heading north and a southward force as the satellite crosses the equator heading south. Because the dynamic system has such a low inherent damping, the tether angle, and thus the lift force, will follow the flap control position very closely. The flap control signal is then the same as the required tether angle.

In Figure 3 is shown a schematic diagram of the geometry of the airfoil position as it varies from the starboard side of the Shuttle to the port side of the Shuttle and back again each orbit. Because of the changing angle of the tether (from 9 to 27 degrees, as shown in Table 2), the tether length λ must be varied cyclically over each orbit from 100.5 to 123.8 km to keep the sail at a constant altitude. With an orbital period of 88 minutes, the maximum tether length rate of change is 27.7 m/s. With a more powerful winch motor, higher rates of tether length change could be used to raise the airfoil to a higher altitude during the zero lift portion of its flight. This would reduce the drag and improve the overall efficiency. It would also allow additional cooling of the vehicle and tether, making possible higher Q operations with the same amount of thermal protection.

The change in tether length required for deployment, retrieval, and maintaining a constant sail altitude causes complex vibrations of the tether to be excited. These unwanted vibrations must be minimized in order to prevent errors in the controlled angle of attack of the deployed sail or large oscillations of the sail during retrieval. The dynamics of the tether with an end mass are discussed in more detail by Modi and Misra.[6]

The simplest control law, shown in Figure 4, is a sinusoidal input that causes the tether angle to peak just as the satellite crosses the equator. For a sail altitude of 93 km, an orbital period of 88 minutes, and a lift force of 329 N, the maximum lateral excursion of the sail on the end of the tether is 52 km, corresponding to a tether lateral angle of 29 degrees. The maximum lateral velocity is then 62 m/sec. This amounts to only a small perturbation on the nominal airspeed of 7 km/sec for the airfoil.

On the left side of Figure 5 is shown the dynamic pressure, Q, on the airfoil as a function of altitude.[14] For an airfoil area of 100 square meters, the precession rate of the space shuttle is shown on the right scale, using 70,000 and 100,000 kg as the mass of the shuttle in a 185-km orbit. The precession rate increases greatly as the airfoil is extended to lower altitudes, but the problems of aerodynamic heating are increased. The larger values of Q would require higher temperature materials for the leading edge of the airfoil, such as the HRSI silica tiles used on the Space Shuttle for temperatures up to 1500K. The precession rate could also be increased by simply increasing the area of the airfoil. Multiple-folding, deployable, or inflatable structures could be used for the larger areas and still fit within the Space Shuttle cargo bay.

III. Satellite Sail versus Synergetic Maneuver

In Figure 6 is shown a comparison of the velocity difference, in km/sec, required to change the orbital plane of the space shuttle various numbers of degrees, using rocket propulsion, using the optimum synergetic aerodynamic maneuver, and using the satellite sail with a lift/drag ratio of three.[9] In the all-propulsive maneuver, the satellite rockets are fired to provide a thrust at right angles to the current orbital velocity. The maneuver is quick, but very costly in fuel because of the high velocity change required. For low orbits, this is a very high velocity. The optimum synergetic maneuver requires that the shuttle fire rockets to dip into the upper atmosphere, then perform an aerodynamic maneuver to provide a side force, then fire rockets to return to the initial orbit. This maneuver is limited in efficiency by the lift-to-drag ratio of the Space Shuttle, which is not optimized for this function, and by the fact that the heavy Shuttle must first be lowered and then raised against gravity.

The use of the satellite sail is the slowest of the three maneuvers, but it is the most efficient. There is no need to de-orbit the shuttle into the upper atmosphere; the much lighter sail is lowered instead. The sail can be designed to provide optimum lift/drag for the chosen altitude. The aerodynamic lift provides the side force to change the orbital plane, and then the sail is raised back to the shuttle; rockets are used to make up for the energy lost to the drag of the sail and tether, which can be much less than that of the entire shuttle vehicle. There is no orbital velocity loss associated with lowering and raising the sail; the center of gravity of the satellite/sail system maintains a constant velocity in a fixed orbit.

IV. Shuttle Operations

The space shuttle is to be launched from two spaceports—Cape Canaveral, Florida, at 28.5 degree inclined orbits, and Vandenberg AFB, California, into polar orbits. If the shuttle is

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given a plane change capability of 31 degrees, inclination from zero (equatorial) to 59.5 degrees, and launches from VAFB can cover inclinations from 59 degrees to 149 degrees (retrograde). A plane change of this largest required magnitude could be accomplished in about 20 days at 1.5 degrees per day, which is a reasonable time for later Shuttle missions. For those missions with lesser orbital plane change required, less time must be spent in the plane-changing maneuver. The deployment and retrieval of the shuttle sail would require additionally about 8 hours and 16 hours, respectively.

The Space Shuttle currently carries additional fuel for orbital maneuvering and stationkeeping. Any extra fuel carried to change the orbital plane would be an additional mass to be lifted by the Shuttle boosters. The use of the Shuttle sail would be an alternative for this extra mass; instead of extra fuel, the sail would be stowed in the cargo bay. As shown in Figure 6, the use of the Shuttle sail requires far less energy than the use of rocket propulsion. The use of the Shuttle sail in routine orbital plane changing and in orbital phasing would allow the use of the Shuttle for scavenging of the debris that now clutters low Earth orbit and presents a hazard to space flight.[15] This operation could be done during each mission that brought the Shuttle within sail range of a known piece of space debris. The sail could be deployed while the Shuttle crew was engaged in other operations, and when the sail brought the Shuttle into the proper position, the debris could be secured in the cargo bay for disposal or for preservation in a museum.

V. A Shuttle-Tethered Hypersonic Research Facility

A further use of the satellite-tethered lifting body would be in gaining fundamental knowledge of the flight conditions at about 100 km altitude and Mach 25. A variety of airfoils or lifting bodies could be instrumented and controlled to provide data over different angles of attack, atmospheric densities, and relative velocities. The regime of operation would encompass extremely long mean free paths for the air molecules and would allow new fundamental aerodynamic data to be obtained. As such a facility, the satellite-tethered lifting body would in essence function as a high-Mach-number, low-pressure wind tunnel for a variety of experimental investigations. In this mode of operation the lift vector would be oriented vertically, so as to provide an upward force on the satellite. This force would counteract some of the drag force tending to lower the satellite orbit. In this configuration, the airfoil need not be symmetric, and it might be equipped with a vertical stabilizer. The vertical stabilizer is not needed in the horizontal lift mode for yaw stability, which is provided by the tether.

The use of the Shuttle-tethered research airfoil or lifting body would be much simpler than changing its orbit plane. The airfoil would be oriented to provide a vertical lift force, thus maintaining the body almost directly below the Shuttle. There would be no need to change the length of the tether during the experiments except for slow changes in altitude to measure flight parameters at different atmospheric densities. There would be fewer dynamic response problems of the tether/sail system, and the retrieval could be a leisurely operation to prevent undue buildup of tether/sail oscillations.

VI. Conclusions

The concept of changing the orbital inclination of a satellite by an airfoil suspended into the atmosphere has been examined. The technique is potentially more efficient than the rocket or the synergetic maneuver for all inclination changes, but it is comparatively slow. Maximum rates of orbital precession of about 1.5 degrees per day appear to be achievable with a light Shuttle, a large, high-lift airfoil, and a high-temperature tether. The Shuttle sail could be folded and stowed in the cargo bay for re-use on a variety of satellite-servicing missions. The concept would also allow the use of the Space Shuttle for long-duration hypersonic aerodynamic studies for a variety of airfoils or lifting bodies at about 100 kilometers altitude and Mach 24. Further study is needed to define the optimum sail size and mass as functions of the Shuttle altitude, inclination change required, and required mission time.

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Table 1 Design Parameters for a Satellite Sail

Satellite Mass (Space Shuttle)	70,000 kg
Satellite Orbit Radius	6563 km
Precession Rate	1.5 deg/day
Sail Orbit Radius	6471 km
Tether Length	92-109 km
Tether Angle	9-27 deg
Orbital Period	88 min
Airfoil Area	100 sq m
Airfoil Structural Mass	700 kg
Airfoil Insulation	627 kg
Airfoil Equipment	173 kg
Airfoil Total Mass	1500 kg
Lower Tether Mass, A-286 Hi-Temp Alloy	364 kg
Upper Tether Mass, 302 Stainless	535 kg
Lower Tether Diameter	1. 72 mm
Upper Tether Diameter	0. 99 mm
Maximum Angle of Attack	10 deg
Maximum Lift Force	329 N
Maximum Drag Force (Including Tether)	110 N
Lift/Drag	3.0
Airfoil Dynamic Pressure, Q	54.4 N/sq m

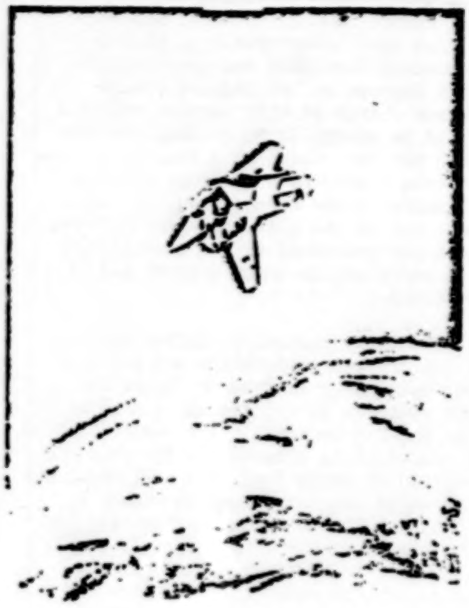

Figure 1. An Artist's Concept of the Satellite Sail.

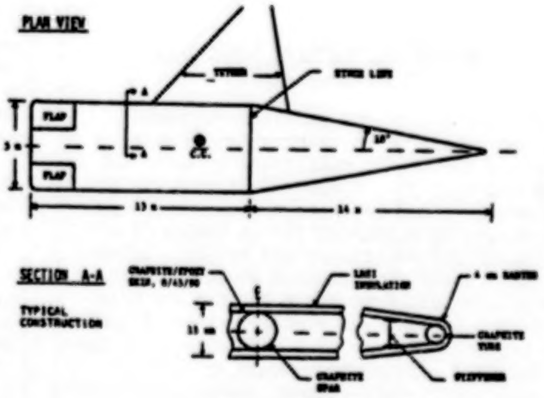

Figure 2. Schematic Diagram of the Airfoil Planform and Typical Cross-Section.

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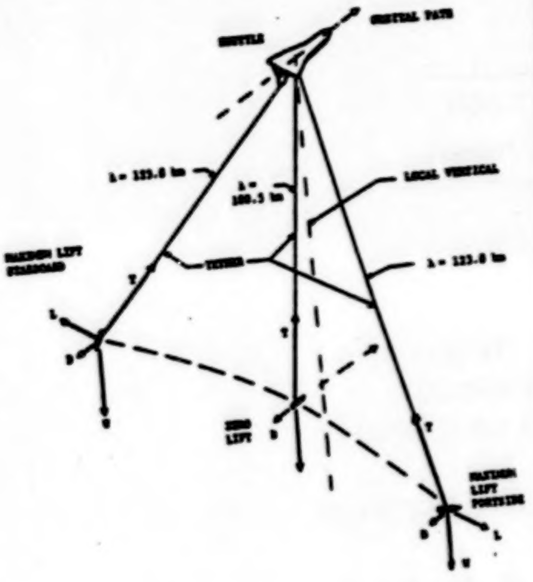
ORBITAL PATH
SHUTTLE
LOCAL VERTICAL
TETHER
MAXIMUM LIFT STARBOARD
ZERO LIFT
MAXIMUM LIFT PORTSIDE
T
L
D
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Figure 3. Shuttle, Tether, and Airfoil Geometry, and Maximum Excursion over One Orbit.

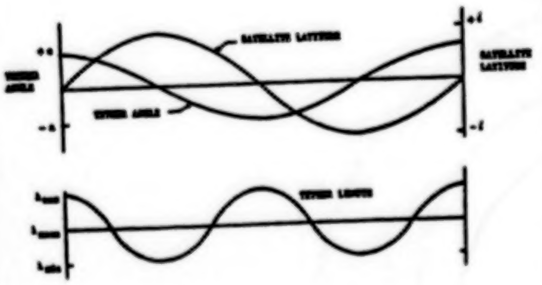


Figure 4. Tether Angle and Length Required as Functions of the Satellite Latitude.

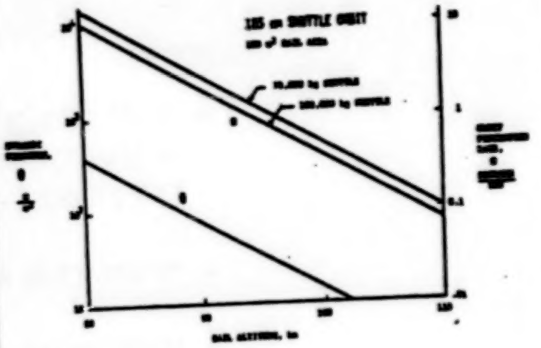


Figure 5. Dynamic Pressure and Shuttle Precession Rate for a 100-Square-Meter Sail.

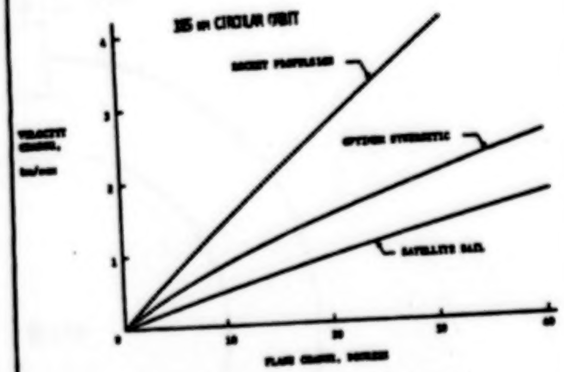


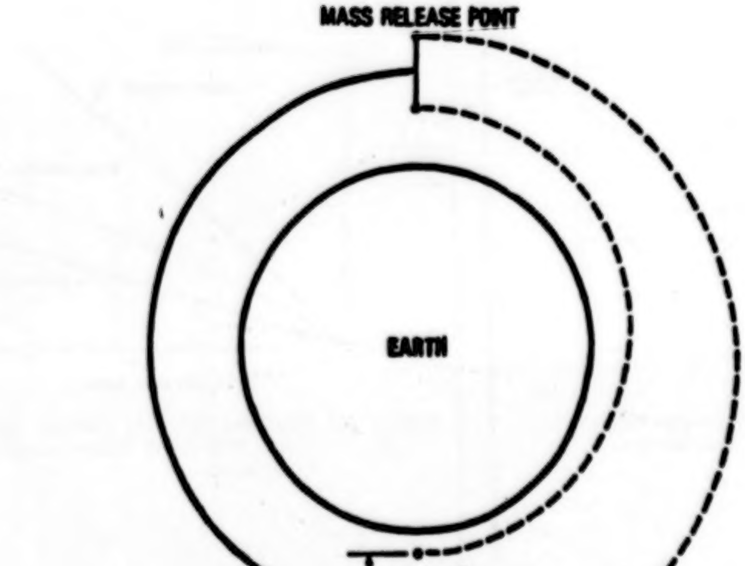
Figure 6. Required Velocity Changes for Three Different Plane-Change Techniques.

PRESENTATION 3

THE USE OF LONG TETHERS FOR PAYLOAD ORBITAL TRANSFER

FUNDAMENTALS

- TO 1ST ORDER IN L/R, CENTER OF MASS OF TETHERED SYSTEM IS UNDISTURBED (BUT 2ND ORDER EFFECTS CAN BE EXPLOITED)
- TETHERS ACT AS MOMENTUM-EXCHANGE DEVICES
- IF POST-RELEASE ORBIT OF LOWER MASS IS RESTORED USING ROCKETS, THE FUEL REQUIRED IS THE SAME AS IF THE UPPER MASS WERE BOOSTED INSTEAD USING THE SAME ROCKETS.


MASS RELEASE POINT
EARTH
MAXIMUM SEPARATION DISTANCE
INITIAL SEPARATION = L
GRAVITY GRADIENT RELEASE = 7L
LIBRATING RELEASE < 14L
SPINNING RELEASE > 25L

SOME CATEGORIES OF ORBIT TRANSFER SCHEMES

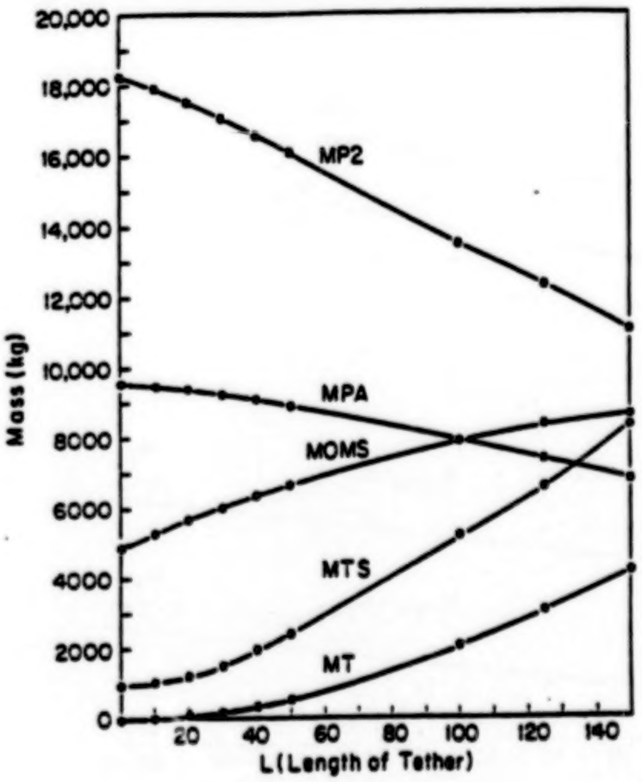
(A) INCREASE PAYLOAD TO SOME HIGHER ORBIT USING OMS SHUTTLE FUEL INSTEAD OF OTV.

(B) USE ALTITUDE LOSS OF BASE AFTER PAYLOAD BOOST AS PART OF REENTRY MANEUVER.

(C) RE-BOOST BASE OVER EXTENDED TIME USING HIGH I_{SP} ENGINES. TRADES TIME FOR PROPELLANT, BUT STILL ACCOMPLISHES FAST TRANSFER.

(D) BOOST STATION BY RELEASING PAYLOADS DOWNWARDS (I.E., REENTERING SHUTTLE CAN BOOST SPACE STATION).

(E) EXPLOIT 2ND ORDER EFFECTS TO MODIFY CENTER OF MASS ORBIT WITH NO MASS EXPULSION.



SHUTTLE BASED TETHER SYSTEM PERFORMANCE. OTV SIZE IS ALLOWED TO VARY TO FILL ALLOWABLE THROW WEIGHT. 100 NM MINIMUM POST-RELEASE PERIGEE.

STS AND EXPENDABLE LAUNCH VEHICLE ESTIMATED CAPABILITIES

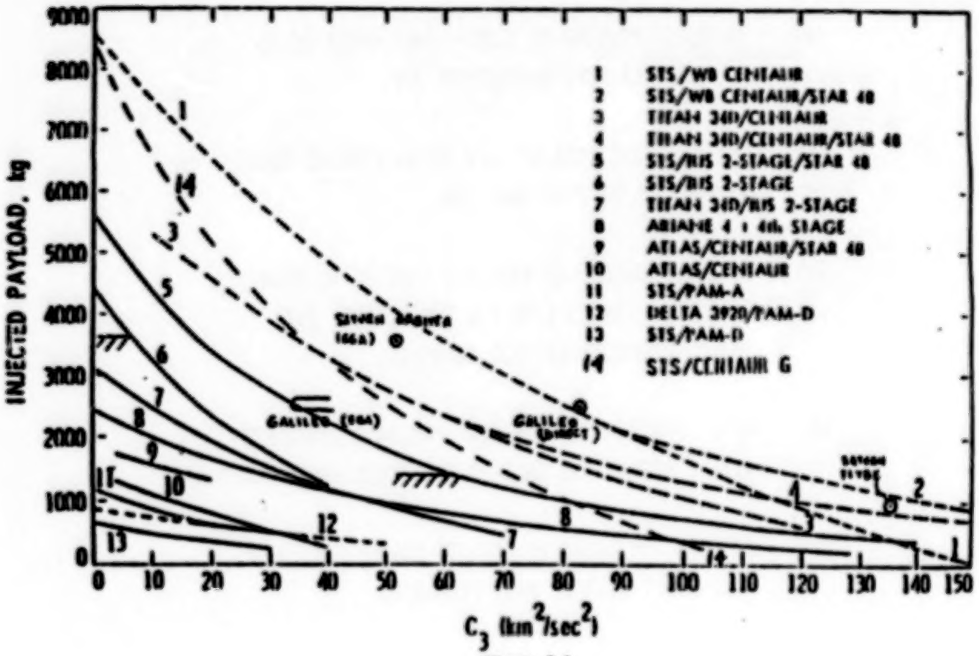
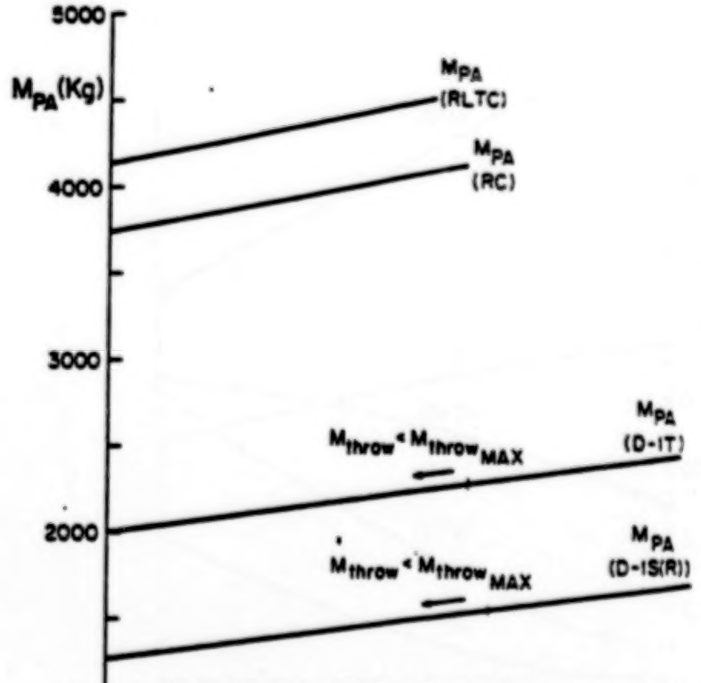


Figure 3.1



GALILEO PAYLOAD MASS VS. TETHER LENGTH FOR FOUR CENTAUR VERSIONS. NOTICE RC AND RLTC EXCEED MAXIMUM THROW WEIGHT.

SPACE-BASED LOW MASS TETHER SYSTEMS

- KEY TO INCREASED USEFULNESS: LEAVE TETHER IN ORBIT. REQUIRES A STRATEGY FOR REUSEABILITY.

- OPERATIONS SEQUENCE:

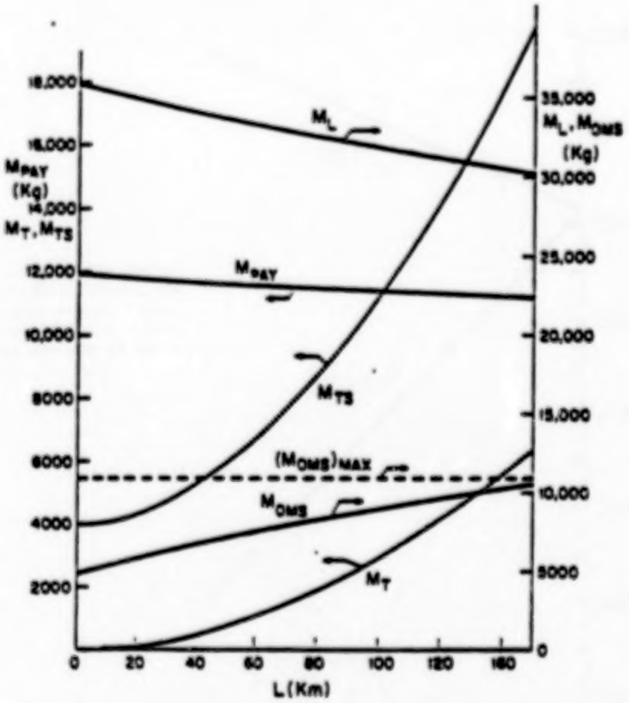
  (A) SHUTTLE DOCKS WITH REWOUND TETHER IN LEO. TETHER SYSTEM MAY BE ~10-15 TON, CAN BE DEPLOYED BY INITIAL SHUTTLE MISSION.

  (B) OTV-MOUNTED PAYLOAD IS ATTACHED TO TETHER UPPER END, TETHER IS UNREELED UNDER SHUTTLE TENSION CONTROL.

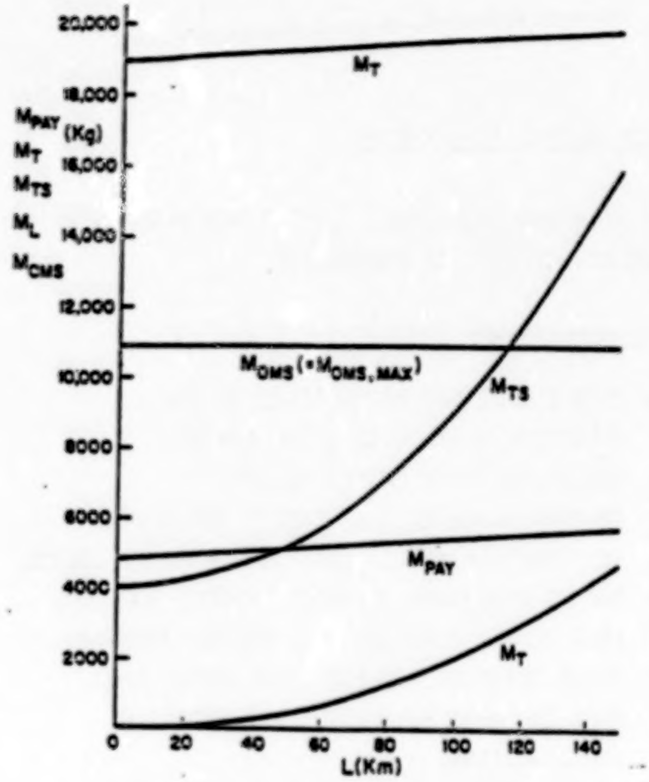
  (C) PAYLOAD IS RELEASED, OTV FIRES. SHUTTLE GOES INTO LOWER ORBIT WITH PERIGEE ABOVE SENSIBLE ATMOSPHERE.

  (D) TETHER IS PARTIALLY REWOUND UNDER SHUTTLE POWER UNTIL C.G. OF TETHER SYSTEM IS (AT APOGEE) AT INITIAL ALTITUDE.

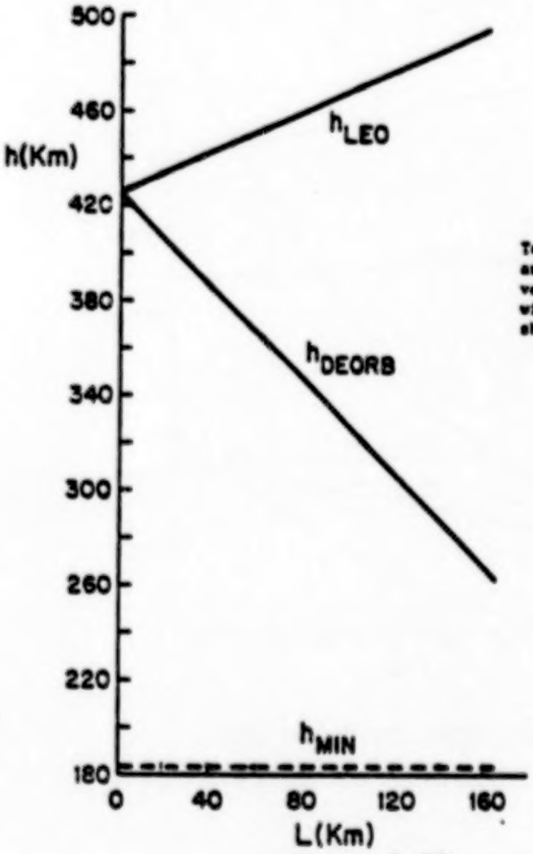
  (E) SHUTTLE DETACHES, REENTERS. TETHER COMPLETES REWINDING UNDER ITS OWN POWER. SYSTEM IS READY FOR REUSE.



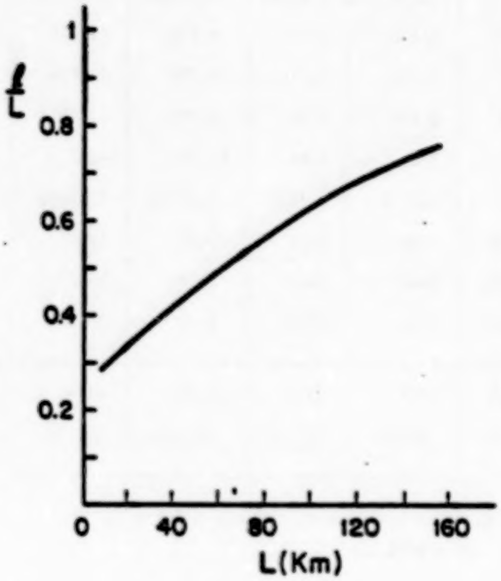
SPACE-BASED TETHER SYSTEM PERFORMANCE
OTV STILL ALLOWED TO FILL THROW WEIGHT



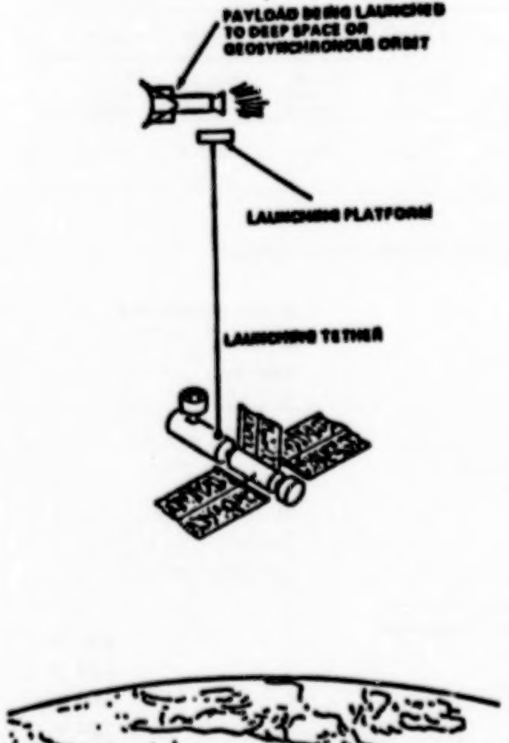
SPACE-BASED TETHER SYSTEM PERFORMANCE
OTV IS FIXED (CENTAUR). FULL OMS LOAD.
POST-DEORBIT PERIGEE VARIABLE (BUT $\geq$ 100 NM).



Tether system parking altitude (h_{LEO}) and lowest shuttle altitude (h_{deorb}) versus tether length for case with fixed OTV, maximum OMS fuel. Also shown is minimum allowable altitude.



Fraction of tether length left deployed at Shuttle detachment (case with fixed OTV and maximum OMS fuel).


PAYLOAD BEING LAUNCHED TO DEEP SPACE OR GEOSYNCHRONOUS ORBIT
LAUNCHING PLATFORM
LAUNCHING TETHER

Tether length (km)	0	100	150	200	250
$\lambda = L/R_{LEO}$	0	0.01477	0.02216	0.02954	0.03693
ν_{MAX}	0	0.273	0.167	0.120	0.0937
ν(adopted)	0	0.182	0.111	0.080	0.0625
M(Tether)/m	0	0.140	0.356	0.711	1.269
M(Platf. only)/m	-	5.35	8.65	11.79	14.73
f	1	1.0125	1.0199	1.02735	1.03476
ΔV_p (m/sec)	2398	2233	2133	2035	1938
ΔV_a (m/sec)	1456	1447	1442	1437	1432
ΔV_{TOT} (m/sec)	3854	3680	3575	3472	3370
M_L (kg)	4409	5009	5312	5684	6076
M_0 (loaded OTV) (kg)	18,509	19,109	19,412	19,784	20,176

} Centaur OTV

Table 4.1 Performance of tether-assisted LEO-GEO system.
$R_{LEO} = 400 + 6370$ km.

Table 4.3 shows calculated results for a 250 Km tether

N		1	10	30	100	300
c_{OPT}(m/sec)		11,420	12,290	14,030	18,900	28,550
$(I_{sp})_{OPT}$(sec)		1,166	1,254	1,432	1,928	2,913
at c_{OPT}	η_p	0.380	0.407	0.455	0.5533	0.6498
	P_{max}(KW) (EOL/BOL)	$\frac{331}{389}$	$\frac{332.3}{390.9}$	$\frac{338.8}{398.6}$	$\frac{315.5}{441.8}$	$\frac{483}{568.2}$
	M_{z_s} (Kg/mission)	1,095	1,018	891.9	662.2	438.4

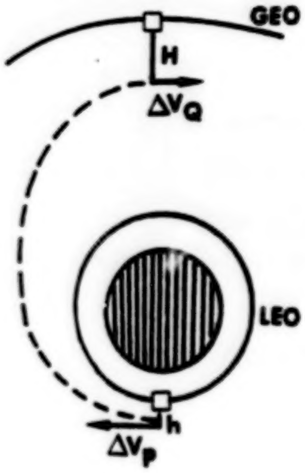
Table 4.4 Platform propulsion system characteristics

Type	Hg ion bombardment	
Diameter per thruster	30 cm	
Specific impulse	2000 sec	
Thrusting time	14 days	
Thrust per unit	0.546 Nt	
Thrust power per unit (including distribution losses)	9.36 Kw	
No. of thrusters required	41 (+ 4 extras)	
Mercury mass per mission	632 Kg	
Solar array power (EOL/BOL)	384.2/452 Kw	
Thrust system mass (thrusters, thermal control, power supplies, interface module structure, etc.)		5464 Kg
Solar array mass		4520 Kg
Solar array gimballing mass		1808 Kg
Solar array regulators mass		2260 Kg
Battery system mass		2113 Kg
Total propulsion related mass		16,165 Kg

OPTIMIZATION OF ION DRIVE FOR PLATFORM ORBITAL MAKE-UP

TWO-TETHER SCHEMES

- FOR TRANSFERS TO HIGH ORBITS (I.E., GEO), CAN USE ADDITIONAL RECEIVING TETHER



- THIS REDUCES ORBITAL PERTURBATION TO PLATFORM AND TETHER LENGTHS
- CAN DESIGN SUCH THAT TRANSFER ORBIT HAS PERIOD COMMENSURATE WITH GEO PERIOD (1/3 DAY, 1/2 DAY, ETC.), TO ALLOW MULTIPLE ATTEMPTS AT RENDEZVOUS.
- CAN USE LEO AND GEO ΔV's OF VARIABLE MAGNITUDE. FOR $\Delta V_p = \Delta V_Q = 0$, H = 1200 KM, H = 10,000 KM

TABLE 9. TRANSFER TO GEO BY TETHER, WITH ΔV's SUPPLIED BY PROPULSION

T = 1/2 day | Upper Tether Length: H = 5913 Km

ΔV_P	ΔV_Q = 600	700	725	750	775	m/s			
600	910/1203	873/257	X	X	X	X	X	X	X
900	718/1396	722/412	X	X	X	X	X	X	X
1200	512/1601	557/378	563/340	X	X	X	X	X	X
1500	293/1820	381/753	397/506	411/267	X	X	X	X	X
2000		62/1072	97/807	128/550	156/302	X	X	X	X
m/s						X	X	X	X
						X	X	X	X

KEY: Entries are h(Km)/Altitude of LEO (Km)

X = LEO altitude < 200 Km
* = h negative

MODIFICATION OF ORBITAL ENERGY BY CONTROL OF TETHER LENGTH

OBJECTIVE: TO EXCHANGE MECHANICAL "REELING" ENERGY FOR ORBITAL CENTER OF MASS ENERGY

CONSTRAINTS:

(A) TOTAL ANGULAR MOMENTUM MUST REMAIN CONSTANT

(B) LIBRATION AMPLITUDE TO REMAIN FINITE

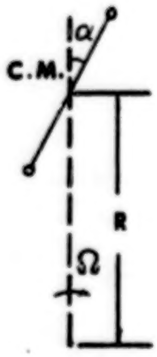
(C) BECAUSE OF (A) AND (B), ORBITAL ANGULAR MOMENTUM WILL REMAIN CONSTANT (IN THE LONG RUN)

EFFECTS: ENERGY, ANGULAR MOMENTUM AND ECCENTRICITY RELATED BY

$$E = -\frac{M\mu^2}{2L^2}(1 - e^2)$$

SINCE L = CONST., INCREASING e INCREASES E AND VICE VERSA (BUT SECOND ORDER EFFECT)

APPROACH: SET UP RESONANT PERTURBATION OF ORBITAL RADIUS USING TETHER LIBRATION



$$L = \underset{\substack{\nwarrow\\ \text{TOTAL}\\ \text{MASS}}}{M}\,\Omega^2 R + \underset{\substack{\uparrow\\ \text{MOMENT OF INERTIA}\\ \text{OF DUMBBELL}}}{I}\,(\Omega + \dot{\alpha})$$

SINCE L = CONST., $\dot{\alpha} \gtrless 0$ IMPLIES

$A \left\{\begin{matrix}\text{DECREASE}\\ \text{INCREASE}\end{matrix}\right\}$ OF Ω

THEN, THE CENTRIFUGAL FORCE $M\Omega^2 R$

ALSO, $\left\{\begin{matrix}\text{DECREASES}\\ \text{INCREASES}\end{matrix}\right\}$

- EFFECT IS TO DRIVE RADIAL EQUATION OF MOTION IN STEP WITH $\dot{\alpha}$

- KEY NOW IS TO FORCE LIBRATION AT ORBITAL FREQUENCY (TO "STACK UP" SUCCESSIVE EFFECTS).

FORCED LIBRATION

DUMBBELL LIBRATION EQ. IS

$$\frac{d}{dt}\left(I\,\frac{d\alpha}{dt}\right) = -3\,I\alpha \quad (\text{SMALL } \alpha)$$

$$I = \frac{m_1 m_2}{m_1 + m_2}\,L^2$$

IF WE FORCE L TO FOLLOW EITHER

$$L = L_{MAX}\,|\cos\Omega t|$$

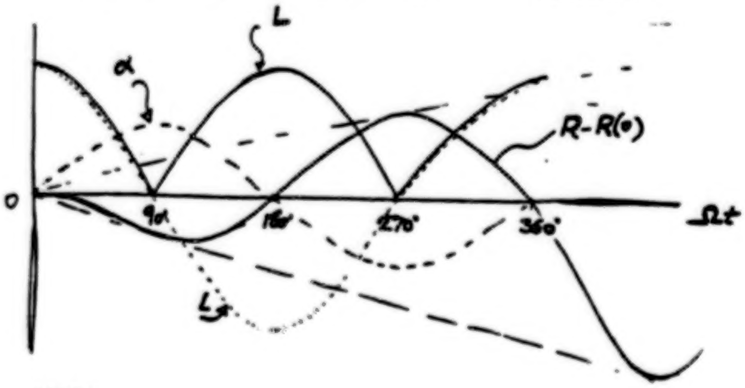
OR

$$L = L_{MAX}\,\cos\Omega t$$

THEN SOLUTION IS

$$\alpha = \alpha_0 \sin\Omega t$$

AND $I\alpha$ HAS HARMONIC AT Ω - RESONANCE



NOTES

- REQUIRES "BOUNCING" OR CRISS-CROSSING AT $V = \Omega L_{MAX}$
- START BY "LAUNCHING" MASS AT SOME α_0, BUT $\left(\frac{d\alpha}{dt}\right)_0 = 0$.
- POINT 90° AHEAD OF LAUNCH WILL HAVE ITS ORBITAL ALTITUDE LOWERED. POINT 90° BEHIND WILL BE RAISED.
- CAN BE USED EITHER TO PRODUCE OR TO CANCEL ECCENTRICITY.
- TETHER IS ALWAYS BEING PULLED ON. TENSION IS ~4/3 STATIC - NO LOSS OF TENSION.

MAGNITUDE

- AFTER N ORBITS, APOGEE RAISING OR LOWERING IS

$$\Delta R = \frac{5\pi}{2} \frac{m_1 m_2}{(m_1+m_2)^2} \left(\frac{L_{MAX}}{R}\right) L_{MAX} \ \alpha_0 \ N$$

FOR $L_{MAX} = 100$ KM , $M_1 = M_2$, $\alpha_0 = 0.25$ RAD

$$\Delta R = 0.9N \text{ KM}$$

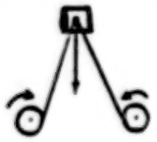
OR 15 KM/DAY

- IF BOUNCING IS USED, IMPACT SPEED IS THEN

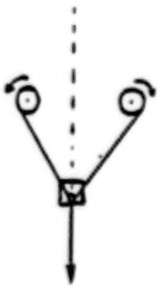
$$V = \Omega L_{MAX} = 100 \text{ M/SEC}$$

NEED GOOD SHOCKS

- BUT CRISS-CROSSING MANEUVER MAY STILL BE O.K.



- DRUMS REVERSE ROTATION AT ZERO TENSION



#4

- TRANSPORTATION PANEL -

GENERAL CONSIDERATIONS

. TETHERS ARE CANDIDATES FOR MANY INTRIGUING TRANSPORTATION APPLICATIONS :

. PAYLOADS TRANSFER TO HIGHER OR LOWER ENERGY ORBITS.

. REENTRY

. RENDEZ-VOUS AND DOCKING.

. ORBIT MODIFICATION BY TETHER CONTROL.

TETHER TELEOPERATOR MANOEUVERING SYSTEM (TTMS) APPLICATIONS

- AT THE PRESENT STAGE A STANDARD TELEOPERATOR IS A SPACE VEHICLE FOR PLACING, RETRIEVING AND SERVICING OTHER SPACECRAFTS.
- A TETHERED TELEOPERATOR CAN ADD INTERESTING FEATURES TO THE STANDARD TELEOPERATOR CAPABILITIES.
- TETHERED TELEOPERATOR PERFORMANCE MUST BE INVESTIGATED IN THE FOLLOWING AREAS :
  - . DEPLOYMENT AND RETRIEVAL OF THE TTMS.
  - . PAYLOAD TRANSFER
  - . REENTRY
  - . RENDEZ-VOUS AND DOCKING.

TETHERED TELEOPERATOR MANOEUVRING SYSTEM EXPECTED PERFORMANCE

o PAYLOAD TRANSFER

. PROVIDE AN ALTERNATIVE SOLUTION TO ORBIT TRANSFER PROBLEMS

. POSSIBLE INCREASE IN LAUNCHING CAPABILITY CONSIDERING THE OVERALL STRATEGY OF THE MISSION.

o RENDEZ-VOUS AND DOCKING

. REDUCE THE PERTURBATIONS ON LARGE BODY STRUCTURES (E.G. S/S) BY MEANS OF THE TETHER MEDIATION.

. EXPEDITE THE RENDEZ-VOUS AND DOCKING MANOEUVRES.

o REENTRY

. REDUCE THE REENTRY VELOCITY OF REENTRY SPACECRAFTS.

TSS CONCEPT FUTURE APPLICATIONS TO NASA SPACE STATIONS

STUDY GENERAL GUIDELINES

WORK STATEMENT. TASKS.

1. ASSESS IF MAJOR WEAKNESSES EXIST WHICH PREVENT THE CONTINUATION OF THE STUDY
2. PROVIDE THE RESULTS IN PARAMETRIC FORM VERSUS THE MAIN PARAMETER VARIATIONS IF THE FIRST POINT IS OVERTAKEN
3. PERFORM SOME PRELIMINARY COMPARISON EVALUATIONS WITH EXISTING SOLUTIONS.

TSS CONCEPT FUTURE APPLICATIONS TO NASA SPACE STATIONS

TETHERED TELEOPERATOR MANOEUVERING SYSTEM (TTMS)

WORK STATEMENT. TASKS.

1. INVESTIGATE ALTERNATIVE PROPOSALS FOR THE TTMS CONTROL SYSTEM.
2. ANALYZE THE JOINT TTMS CONTROL BY TETHER AND AUTONOMOUS TTMS CONTROL SYSTEM.
3. EVALUATE THE MANOEUVERABILITY PERFORMANCE.
4. VERIFY THE MANOEUVRE TIMES AND THE STATION-KEEPING AUTONOMY VERSUS OUT-OF-VERTICAL POSITIONS REACHED.
5. EVALUATE THE ENERGY CONSUMPTION FOR THE MANOEUVERS AND THE STATION-KEEPING.

TSS CONCEPT FUTURE APPLICATIONS TO NASA SPACE STATIONS

DEPLOYMENT AND RETRIEVAL

WORK STATEMENT. TASKS

1. INVESTIGATE SUITABLE CONTROL LAWS FOR THE DEPLOYMENT, RETRIEVAL, STATION-KEEPING PHASES.
2. PROPOSE SOLUTIONS AND INVESTIGATE THE PERFORMANCE OF THE TTMS. CONTROL SYSTEM IF ACTIVELY CONTROLLED.
3. EVALUATE THE ENERGY REQUIRED OR THE PROPELLANT CONSUMED BY THE TTMS CONTROL SYSTEM.
4. EVALUATE THE TETHER CHARACTERISTICS: MATERIALS, MASS, SHAPE, DIAMETERS, ETC.
5. EVALUATE THE POWER REQUIRED BY THE REEL MOTOR.
6. EVALUATE THE RETRIEVAL DYNAMICS IN THE CASE OF LARGE BOTH IN-PLANE AND OUT OF-PLANE INITIAL ANGULAR VALUES RELEVANT TO A RECOVERY OF A TETHERED TELEOPERATOR IF A FAILURE OF THE ACTIVE CONTROL SYSTEM HAS OCCURRED.

TSS CONCEPT FUTURE APPLICATIONS TO NASA SPACE STATIONS

PAYLOAD TRANSFER TO HIGHER OR LOWER ENERGY ORBITS AND [illegible]

WORK STATEMENT. TASKS.

1. DETERMINATION OF THE RANGE OF ORBITS THAT CAN BE ACHIEVED AS A FUNCTION OF TETHER LENGTH BOTH IN THE CASE OF A HANGING AND SWINGING TETHER. INITIAL CONDITIONS ARE THE POSITION AND VELOCITY OF THE SUBSATELLITE AT THE MOMENT OF RELEASE.
2. INVESTIGATION OF THE CONTROL STRATEGIES ALLOWING TO REACH THE ENVISAGED INITIAL CONDITIONS. DETERMINATION OF CONSTRAINTS ARISING FROM DEPLOYMENT/ RETRIEVAL REQUIREMENTS.
3. EFFECTS OF THE RELEASE OF PAYLOAD ON THE ORBIT OF THE MAIN STATION. OPTIMIZATION OF THE STRATEGY OF MANOEUVRES WITH REGARD TO THE STATION-KEEPING OF THE PLATFORM.
4. BEHAVIOUR OF THE TENSION OF THE TETHER AFTER PAYLOAD RELEASE.

TSS CONCEPT FUTURE APPLICATIONS TO NASA SPACE STATIONS

5. EVALUATION OF THE UNCERTAINTY IN ACHIEVING THE DESIRED INITIAL CONDITIONS FOR PAYLOAD RELEASE DUE TO THE BEHAVIOUR OF THE TETHERED SYSTEM.
   SENSITIVITY ANALYSIS WITH REGARD TO THE ELEMENTS OF THE TRANSFER ORBIT.

6. SINGLE OUT AND ANALYZE POSSIBLE STRATEGIES FOR A TETHER INITIATED REENTRY.

TSS CONCEPT FUTURE APPLICATIONS TO NASA SPACE STATIONS

RENDEZ-VOUS AND DOCKING

WORK STATEMENT. TASKS.

1. INVESTIGATION ON THE TIME CONSTRAINTS AND THE RELATIVE VELOCITY VARIATION DURING THE CLOSE APPROACH FOR DIFFERENT TRANSFER ORBITS (DIFFERENT TETHER LENGTHS)

2. ANALYSIS OF THE EFFECT OF THE ORBIT PARAMETERS DISPERSION ON THE RENDEZ-VOUS.

3. INVESTIGATE THE NEED FOR A GOOD MANOEUVRABILITY OF THE DOCKING PROBE TO INCREASE THE RENDEZ-VOUS SUCCESS.

4. EVALUATION OF THE ORBIT AND ATTITUDE PERTURBATIONS OF THE SYSTEM AFTER DOCKING.

MAGNITUDE

- AFTER N ORBITS, APOGEE RAISING OR LOWERING IS

$$\Delta R = \frac{3\pi}{2} \frac{m_1 m_2}{(m_1 + m_2)^2} \left(\frac{L_{MAX}}{R}\right) L_{MAX} \, \alpha_0 \, N$$

FOR $L_{MAX} = 100$ Km , $m_1 = m_2$, $\alpha_0 = 0.25$ RAD

$$\Delta R = 0.9N \text{ Km}$$

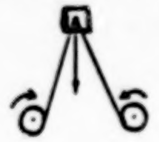
OR 15 Km/DAY

- IF BOUNCING IS USED, IMPACT SPEED IS THEN

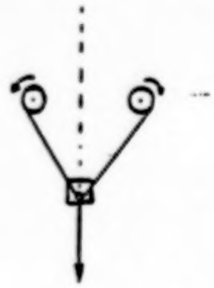
  $V = \Omega L_{MAX} = 100$ m/sec

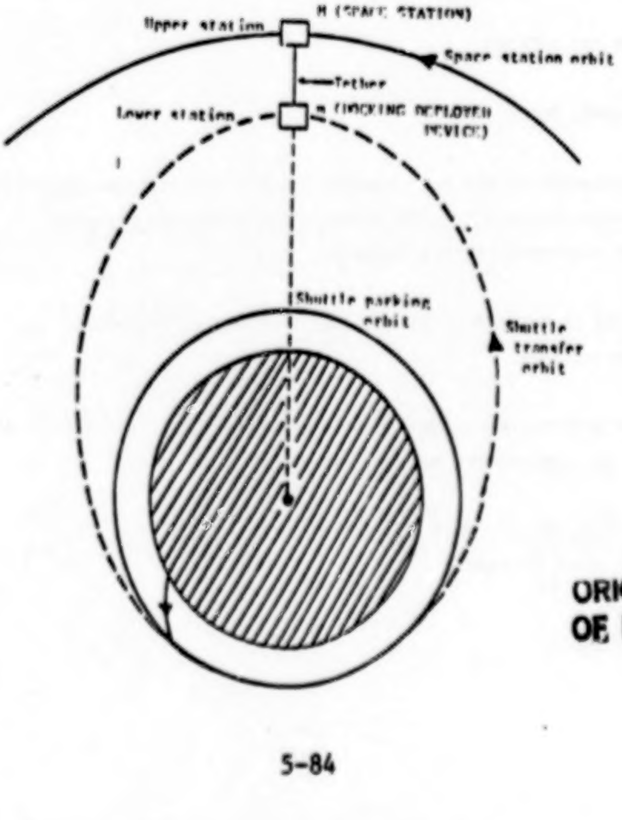
  NEED GOOD SHOCKS

- BUT CRISS-CROSSING MANEUVER MAY STILL BE O.K.



- DRUMS REVERSE ROTATION AT ZERO TENSION




M (SPACE STATION)
Upper station
Space station orbit
Tether
Lower station
m (DOCKING DEPLOYED DEVICE)
Shuttle parking orbit
Shuttle transfer orbit

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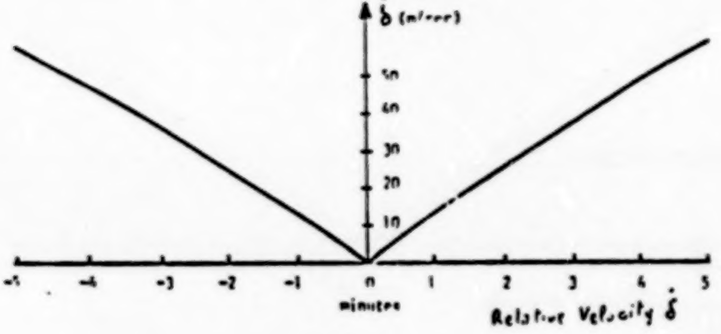

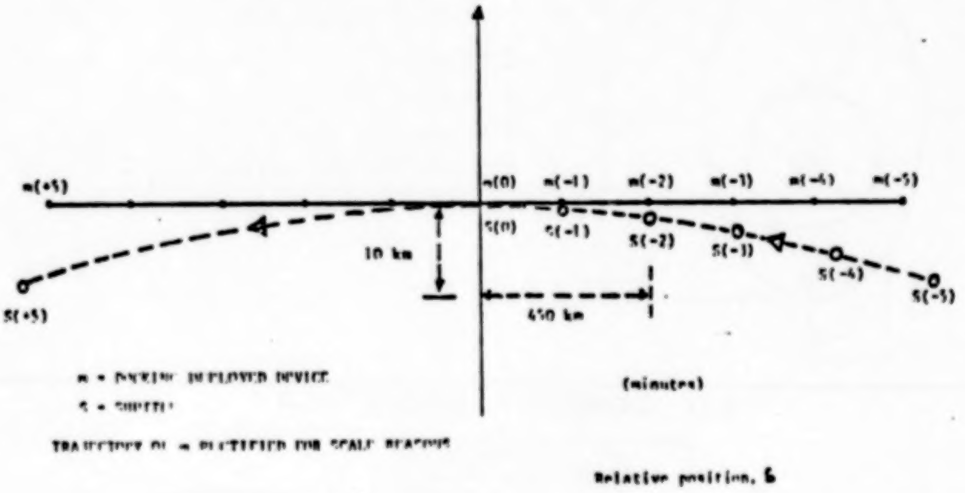
m(+5)
m(0)
m(-1)
m(-2)
m(-3)
m(-4)
m(-5)
S(0)
S(-1)
S(-2)
S(-3)
S(-4)
S(-5)
S(+5)
10 km
450 km
m = DOCKING DEPLOYED DEVICE
S = SHUTTLE
TRAJECTORY OF m RECTIFIED FOR SCALE REASONS
(minutes)
Relative position, δ

STATION KEEPING AND ORBIT PARAMETERS MODIFICATION
(GENERAL CONSIDERATIONS AND PRESENT STATUS)

o **SCOPE**

- INVESTIGATE THE POSSIBILITY TO MODIFY THE ORBIT PARAMETERS BY INCREASING THE TOTAL ENERGY OF THE SYSTEM BY SUITED LENGTH CONTROL OF THE TETHER.

o **AN EXAMPLE**

- THE TETHER OF A TETHERED SS FOLLOWING AN ELLIPTICAL ORBIT CAN BE LENGTHENED AT THE APOGEE AND SHORTENED AT THE PERIGEE OF THE SAME AMOUNT PRODUCING A TOTAL ENERGY INCREASE OF THE SYSTEM. CONSEQUENTLY THE ECCENTRICITY INCREASES.
  THIS STRATEGY COULD PROVIDE AN ALTERNATIVE SOLUTION TO COUNTERACT THE AERODYNAMIC EFFECT OF THE SS WHICH REDUCES THE ORBITAL ECCENTRICITY.

o **PRESENT STATUS**

- THE SOLUTION IS NOW CONSIDERED LITTLE PROMISING.
- ORBIT ECCENTRICITY INCREASE WITH BOTH APOGEE INCREASE AND PERIGEE DECREASE SEEMS TO BE ACHIEVABLE ONLY.

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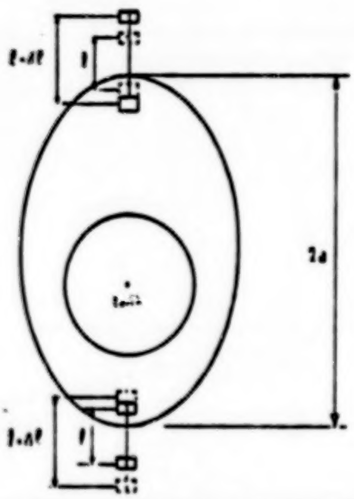
Energy Pumping Example


ℓ+Δℓ
ℓ
2a
Earth
ℓ+Δℓ
ℓ

Energy $= -\frac{K}{2a}$ (increase by pumping)

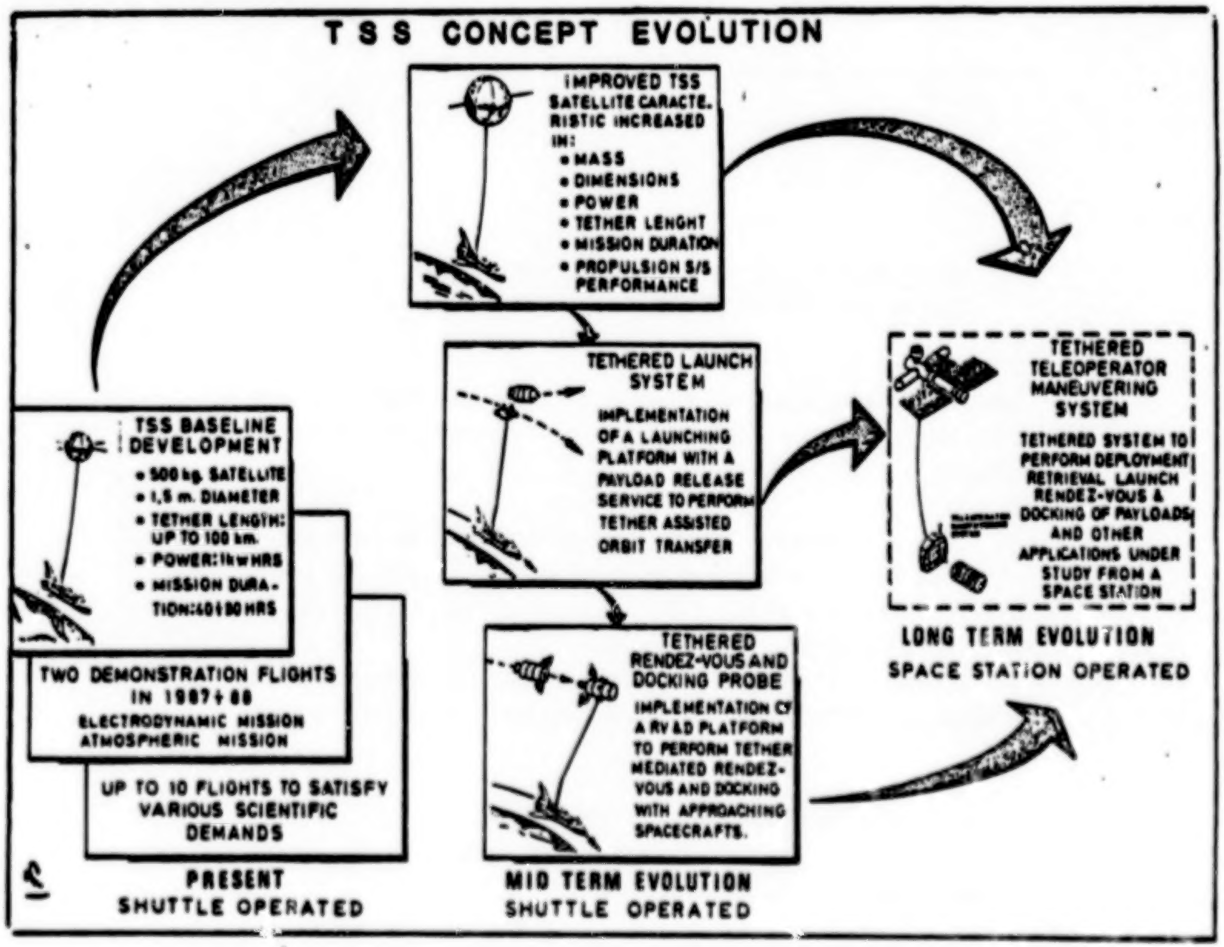
Angular Momentum $= \sqrt{K\,a\,(1 - \ell)}$ = cont.

Results:

a increase

ℓ increase

$a\,(1 + \ell)$ increase (apogee)


T S S CONCEPT EVOLUTION
IMPROVED TSS
SATELLITE CARACTE. RISTIC INCREASED IN:
• MASS
• DIMENSIONS
• POWER
• TETHER LENGHT
• MISSION DURATION
• PROPULSION S/S PERFORMANCE
TETHERED LAUNCH SYSTEM
IMPLEMENTATION OF A LAUNCHING PLATFORM WITH A PAYLOAD RELEASE SERVICE TO PERFORM TETHER ASSISTED ORBIT TRANSFER
TETHERED TELEOPERATOR MANEUVERING SYSTEM
TETHERED SYSTEM TO PERFORM DEPLOYMENT RETRIEVAL LAUNCH RENDEZ-VOUS & DOCKING OF PAYLOADS AND OTHER APPLICATIONS UNDER STUDY FROM A SPACE STATION
TSS BASELINE DEVELOPMENT
• 500 kg. SATELLITE
• 1,5 m. DIAMETER
• TETHER LENGTH: UP TO 100 km.
• POWER: 1kwHRS
• MISSION DURATION: 40÷80 HRS
TWO DEMONSTRATION FLIGHTS IN 1987÷88
ELECTRODYNAMIC MISSION
ATMOSPHERIC MISSION
UP TO 10 FLIGHTS TO SATISFY VARIOUS SCIENTIFIC DEMANDS
TETHERED RENDEZ-VOUS AND DOCKING PROBE
IMPLEMENTATION OF A RV&D PLATFORM TO PERFORM TETHER MEDIATED RENDEZ-VOUS AND DOCKING WITH APPROACHING SPACECRAFTS.
LONG TERM EVOLUTION
SPACE STATION OPERATED
PRESENT
SHUTTLE OPERATED
MID TERM EVOLUTION
SHUTTLE OPERATED

N85-20365

REPORT OF THE
ARTIFICIAL GRAVITY PANEL

ARTIFICIAL GRAVITY PANEL

George Butler Co-Chairman	McDonnell Douglas
Bob Freitag Co-Chairman	NASA Headquarters
Dox Doxiadis	Rockwell
Dave Criswell	Calspace
Charles Tang	JPL
Dennis Fielder	NASA/JSC
John Gille	Martin Marietta
Paul Penzo	JPL
Ken Kroll	NASA/JSC
Luigi Napolitano	University of Naples
Troy Crites	Aerospace
Joe Tschirgi	McDonnell Douglas
Thomas Taylor	Taylor and Associates
Joe Carroll	Calspace
Klaus Reiwartz	ESA-ESTEC-Netherlands
David Yoel	Boeing Aerospace
Robert Conover	NASA Headquarters
Bryant Cramer	NASA Headquarters

I. INTRODUCTION

Space Stations and Tethers

The working group should emphasize the relationship between tether and space station. Tethers can be embodied into NASA's future space station development both as an experimental facility and as a technology for systems enhancement (including attitude control, power source, stationkeeping, friction induction, traction enabling, docking, deployment, etc.).

Early action should be taken to ensure that the basic tether system be baselined into the initial space station architecture and that further concept studies be arranged to embody this basic capability. In the short term, 1991 through 1995, the application of tether techniques would be similar to those employed on intervening space shuttle missions. Space station tethered satellite operations would be continuous, subject to need and occasional association with local spacecraft operations in the proximity of the space station. The use of the tether principles would be further explored for attitude control and/or attitude stabilization damping, proximity operations, etc.

For new tether uses, action should be taken to look at the tether for holding storage uses, proximity operations, and for extension of the capabilities of attached payloads systems. These applications should emphasize dynamic off-vertical tethers, rapid deployment, active-steered tethers, tether-boom combinations, and other concepts.

The artificial gravity group approached this in several ways including:

- A tethered microgravity lab
- A tethered tank farm
- Tethered modules for space station [(antenna farms, docking modules, nuclear power systems, etc.) see Figs. 1 and 2].

APPROACH:

- DEFINE ARTIFICIAL GRAVITY GENERAL REQUIREMENTS
- DETERMINE MOST APPROPRIATE MEANS OF FULFILLING REQUIREMENTS—TETHERS VS. OTHER
- EMPHASIS ON TETHERED SPACE STATION APPLICATIONS

GENERAL REQUIREMENTS:

- MEDICAL/PHYSIOLOGICAL
- TECHNOLOGY
  - FLUID STORAGE AND TRANSFER
  - SUBSYSTEMS
- MICROGRAVITY SCIENCES
  - LIFE SCIENCES
  - MATERIAL SCIENCES/PROCESSES
  - FLUID SCIENCE
  - SIMULATIONS/CHEMISTRY/PHYSICS
- HABITABILITY/PRODUCTIVITY
- OPERATIONS

Figure 1. Artificial Gravity Panel Approach and General Requirements

MEANS:

- MEDICAL: VARIABLE GRAVITY FACILITY ($>10^{-3}$)
- TECHNOLOGY: MANNED R&D FACILITY
- MICROGRAVITY: VARIABLE GRAVITY FACILITY ($<10^{-3}$)
- HABITABILITY: ROTATING SYSTEM (>0.10 G'S)
- OPERATIONS:
  - TANK FARM
  - ANTENNA/SENSOR FARM
  - TMS/OTV RETRIEVAL

Figure 2. Artificial Gravity Panel Means

Not envisaged for the initial space station, but not precluded as a sponsored investigation is the need to investigate artificial G as a requirement for continuous manned habitation of the space station. Sensible "g" levels would require tethered displacement of large elements of the space station configuration.

For long term space station evolutionary development, the consideration of more complex tethering concepts (constellations, launches, etc.) should be investigated including large scale utilization of tethered systems (tank deorbiting, on-orbit uses of external tanks, etc.).

The aforementioned recommendations are summarized in Fig. 3. Figures 4 and 5 summarize the artificial gravity alternative with and without tether. The remaining figures (Figs. 4 through 12) illustrate artificial gravity concepts. Requirements and the means for achieving artificial gravity will be discussed in Secs. II and III.

RECOMMENDATIONS:

- SPACE STATION TETHERED APPLICATIONS
  - NEAR TERM (1991-1995)
    - EXPERIMENTS FROM STATION
    - EXPERIMENTS FROM PLATFORM
    - TETHER SUPPORT OPERATIONS
      - STOWAGE
      - PROXIMITY OPERATIONS
  - MID TERM
    - SYSTEMS CONTRIBUTIONS TO STATION
      - TANK FARM
      - ANTENNA FARM
      - TETHERED RETRIEVAL
  - LONG TERM
    - ARTIFICIAL "G" AS A STATION CHARACTERISTIC
    - LARGE SCALE TETHER OPERATIONS

Figure 3. Artificial Gravity Panel Recommendations

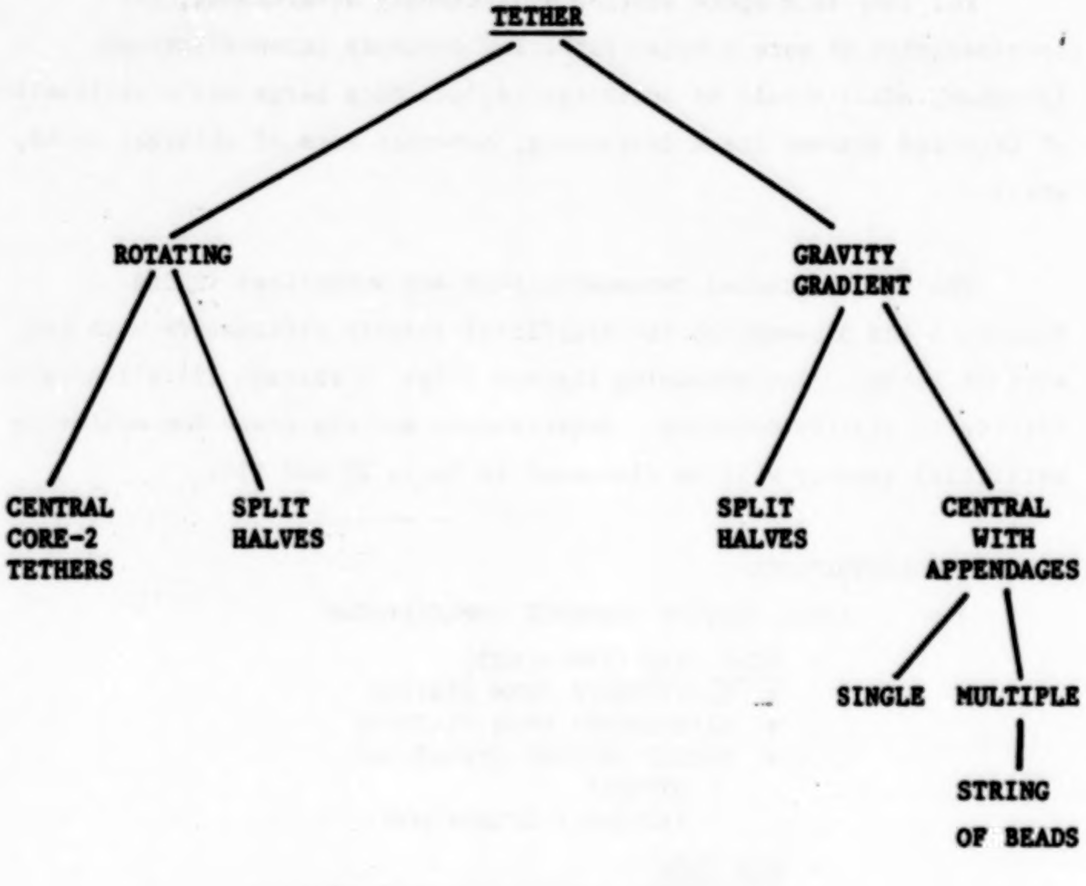

TETHER
ROTATING
GRAVITY GRADIENT
CENTRAL CORE-2 TETHERS
SPLIT HALVES
SPLIT HALVES
CENTRAL WITH APPENDAGES
SINGLE
MULTIPLE
STRING OF BEADS

Figure 4. Artificial Gravity Alternatives (With Tether)

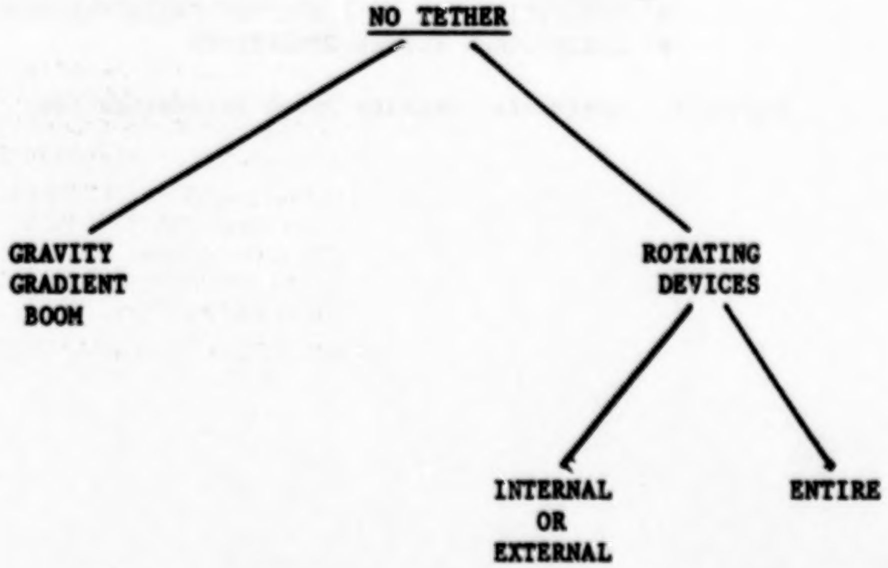

NO TETHER
GRAVITY GRADIENT BOOM
ROTATING DEVICES
INTERNAL OR EXTERNAL
ENTIRE

Figure 5. Artificial Gravity Alternatives (Without Tether)

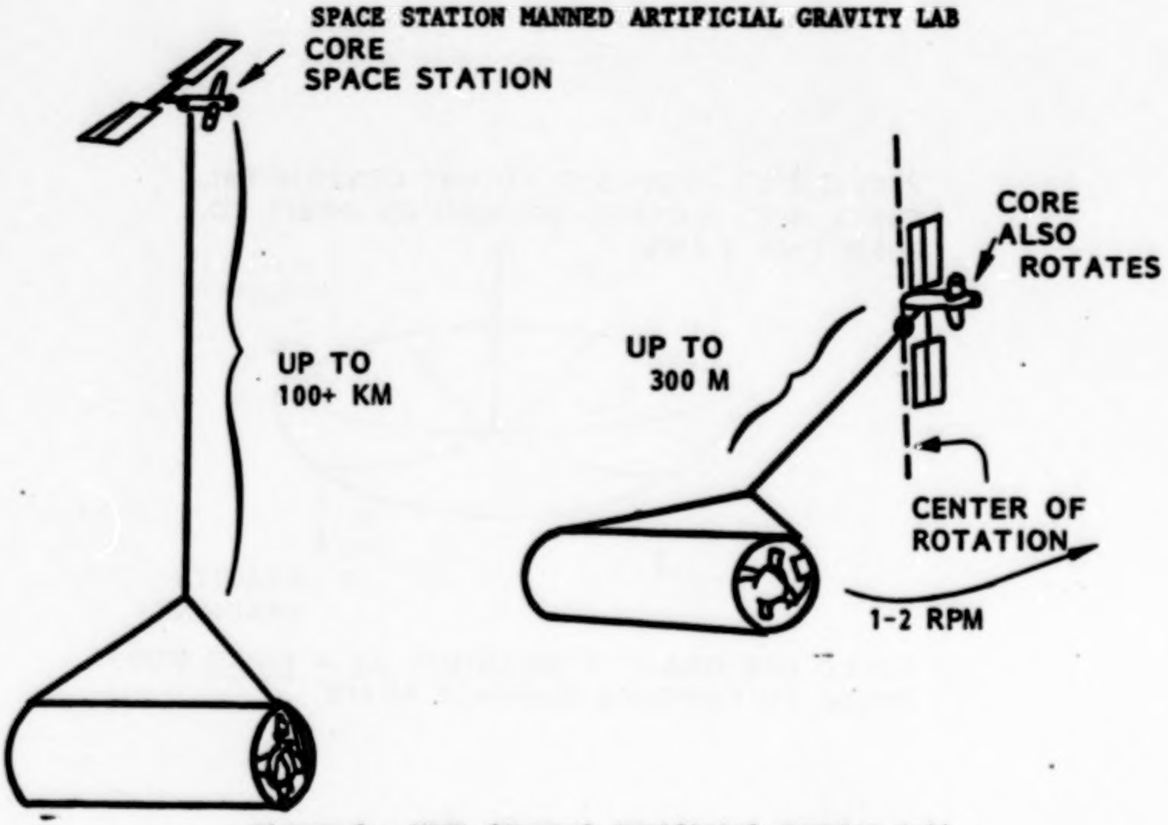
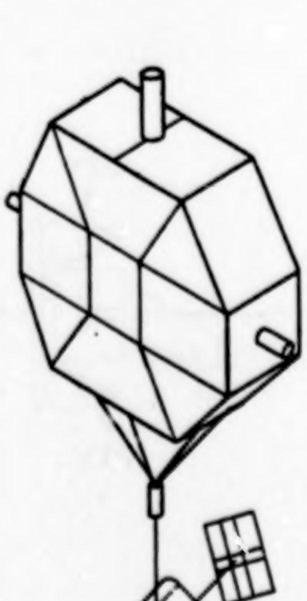

SPACE STATION MANNED ARTIFICIAL GRAVITY LAB
CORE
SPACE STATION
UP TO
100+ KM
UP TO
300 M
CORE
ALSO
ROTATES
CENTER OF
ROTATION
1-2 RPM

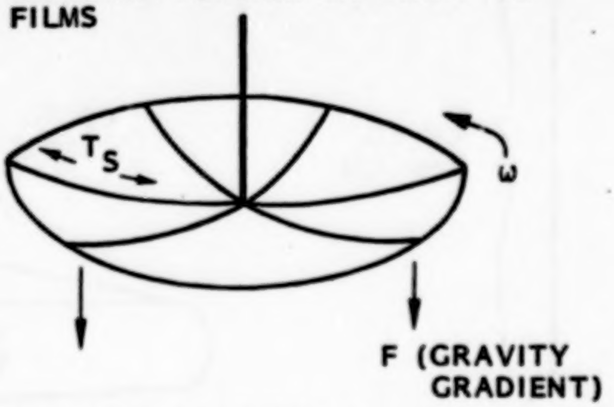
Figure 6. MAGL (Manned Artificial Gravity Lab)



- MODULAR
  - SHUTTLE LAUNCHED
- SERVICEABLE
  - CONTROLLED FROM SPACE STATION
  - INSERT RAW MATERIALS CARTRIDGES
  - REMOVE PROCESSED CARTRIDGES
  - OCCASIONALLY REFURBISHED AT SPACE STATION
- VARIABLE G (CHANGE TETHER LENGTH)
  - LOW G MELT WITH ZERO G SOLIDIFICATION
  - LOW G MELT WITH VARIABLE G SOLIDIFICATION
- ORBIT DECAY PROVIDES ELECTRICAL POWER

Figure 7. Microgravity Materials Processing

PREVIOUSLY PROPOSED TO USE CENTRIPITAL FORCE AND SURFACE TENSION ON ORBIT TO FORM THIN FILMS


T_S
ω
F (GRAVITY GRADIENT)

COULD USE GRAVITY GRADIENT AS A THIRD BODY FORCE TO CONTROL SURFACE SHAPE

Figure 8. Aid in Forming Reflectors

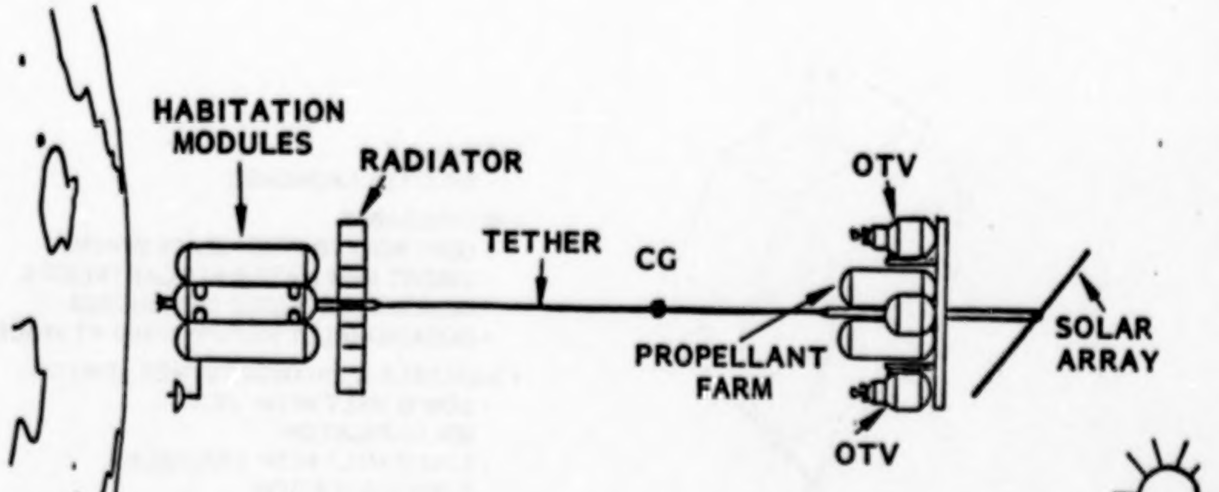

HABITATION MODULES
RADIATOR
TETHER
CG
OTV
PROPELLANT FARM
SOLAR ARRAY
OTV

Figure 9. Tethered Orbital Refueling Space Station

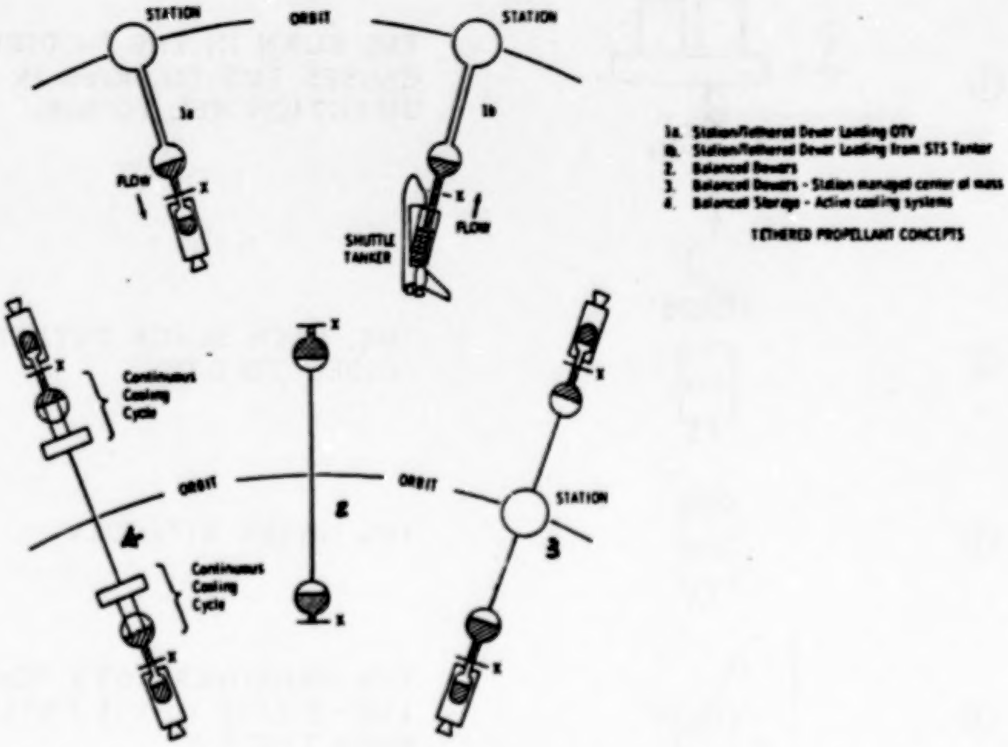

STATION
ORBIT
STATION
1a
1b
FLOW
X
X
FLOW
SHUTTLE
TANKER
1a. Station/Tethered Dewar Loading OTV
1b. Station/Tethered Dewar Loading from STS Tanker
2. Balanced Dewars
3. Balanced Dewars - Station managed center of mass
4. Balanced Storage - Active cooling systems
TETHERED PROPELLANT CONCEPTS
X
Continuous
Cooling
Cycle
X
ORBIT
ORBIT
STATION
4
2
3
Continuous
Cooling
Cycle
X
X
X
X

Figure 10. Tank Farm

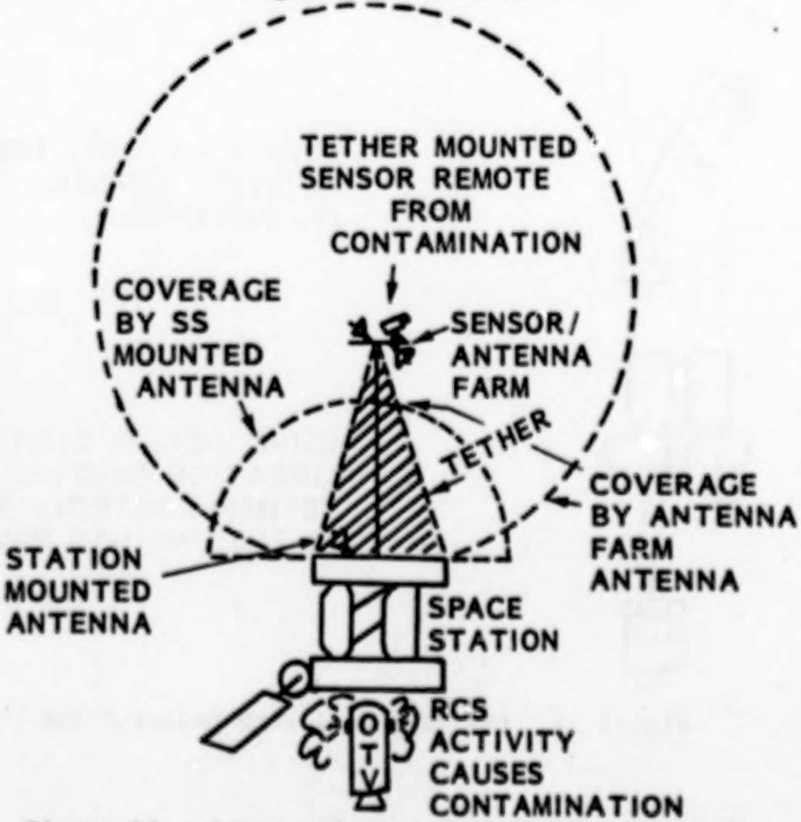
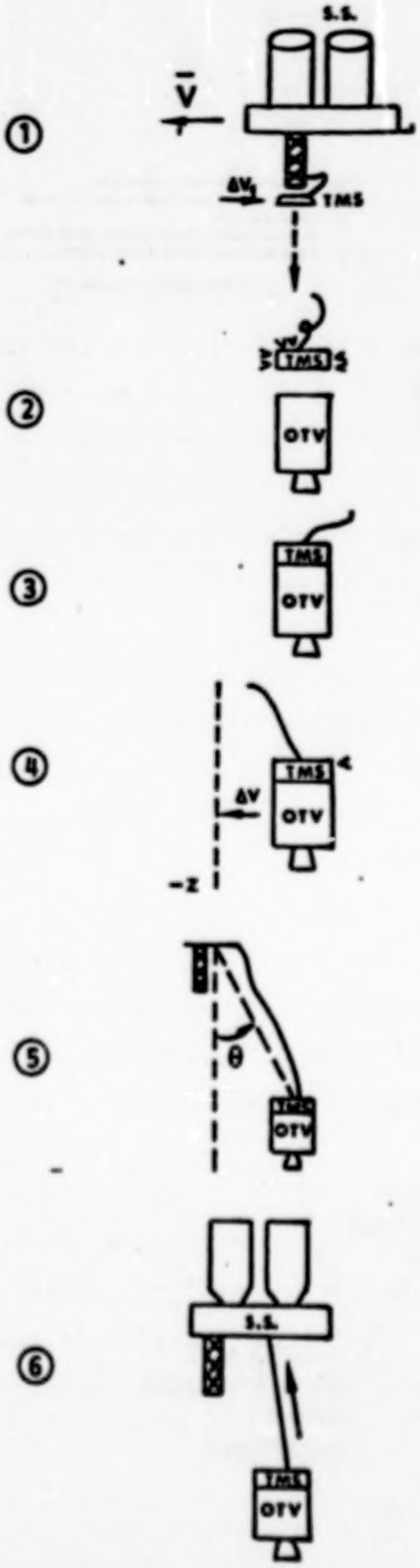

TETHER MOUNTED
SENSOR REMOTE
FROM
CONTAMINATION
COVERAGE
BY SS
MOUNTED
ANTENNA
SENSOR/
ANTENNA
FARM
TETHER
COVERAGE
BY ANTENNA
FARM
ANTENNA
STATION
MOUNTED
ANTENNA
SPACE
STATION
OTV
RCS
ACTIVITY
CAUSES
CONTAMINATION

Figure 11. Antenna Sensor Farm (Tether-Mounted)



① TMS BURN IN THE -V DIRECTION CAUSES TMS TO MOVE IN -Z DIRECTION REL TO S.S.

② TMS, WITH SLACK TETHER IS GUIDED TO OTV

③ TMS MATES WITH OTV

④ TMS MANEUVERS OTV TOWARDS THE -Z LINE (L.V.) EXTENDING FROM THE S.S.

⑤ WHEN θ < (TBD), TMS JET ACTIVITY CEASES. TETHER IS TAUTENED

⑥ USING ACTIVE CONTROL FOR LIBRATION DAMPING, THE TETHER CONTROLLER REELS IN THE TMS-OTV PAYLOAD

Figure 12. OTV Retrieval with Tethered TMS

II. REQUIREMENTS

Artificial Gravity (AG) Medical/Physiological

The use of an artificial gravity to reduce/eliminate the deleterious effects of the zero-g environment on humans. The principal organ systems known to be clearly affected by the loss of a 1-g bias are the cardiovascular, vestibular, and skeletal. The objective is to create an environment or habitat at a g-level appropriate to diminish these effects. This may be continuous exposure to a low-g (0.1-0.5) environment or limited (1-10 hours) exposures (e.g., sleeping/recreation hour) to a higher-g (0.5-2) environment.

The ability to achieve these accelerations while limiting both coriolis and gravity gradient effects will probably require rotating tether systems due to present technology limitations which cause tether weights to become excessive in GG forces of this magnitude.

While the need to research these subjects (e.g., vestibular adaptation, skeletal decay, etc.) is clear (and is covered under microgravity life sciences), the present data does not contain a compelling and immediate need for such a system. (See "Medical Support for Long Duration Missions," IAF, September 1982, Paris, France, Furokaiva et al.)

While artificial gravity may provide effective countermeasures to zero-g—the operational problems (decking, rotation stability, power transfer, etc.) associated with the attainment of significant g levels may far outweigh other countermeasures (e.g., fluid intake, autogenic feedback training, treadmills, etc.).

While skeletal problems are clearly only a problem on long duration (>9 month) missions, the cardiovascular and vestibular problems affect even short term space travelers; and while the cardiovascular problem increases with increasing mission duration, the vestibular problems are almost non-existent for long duration missions (except possibly during reentry). The ability to provide adequate A.G. countermeasures for short term shuttle crewmembers (who have a full mission to carry out) may be impractical.

The need for A.G. for medical/physiological reasons aboard a space station needs further study and must be traded with operational and science needs. This research is presently funded through both NASA/JSC and USAF/AMD.

The shuttle operational constraints and limited stay time will severely limit the capability to evaluate the effectiveness of A.G. countermeasures. A free flying tether system deployed from the shuttle and later retrieved, or deployed from a space station, would be required to support adequate evaluation. The system would need separate power and attitude control as well as the capability to rotate in order to reach the necessary g loads. It would not necessarily need to support manned experiments. However, small primates (Rhesus monkeys) would be desirable. (These issues are covered further under life science experiments.)

Habitability/Productivity

Because of man's evolution in a 1-g environment and our extensive knowledge of 1-g environmental design, we have not yet mastered the zero-g environment as well as may be possible. There may be many ways to improve man's productivity and general comfort (habitability) with A.G. This could include: toilet use, food preparation and eating, water handling, showers, applying torques, moving about, handling supplies, etc. It should be noted that there are specific advantages to a zero-g design. Water immersion facility tests (Ref.: MIT Space Systems Lab Studies) have shown higher productivity rates in zero-g than 1-g. In addition, zero-g designs have a better volume efficiency than 1-g designs (e.g., no floors required, open spaces feel larger, etc.). The extension of these ideas to partial-g environment needs further study.

While the above has discussed in a general manner the thoughts encompassed by habitability, the requirement for zero-g environments for habitability/productivity reasons does not yet exist. Further study (much of which can be ground-based experimentation) is clearly needed to justify any tether applications in this field.

Fluid Storage and Transfer Requirements

A tether system for storing and transferring liquid must primarily position and maintain fluid over the tank outlet. This should also provide for easier quantity gaging. The tether should provide separation of the tank farm from the space station to provide hazard clearance from explosion and contamination. The tether should provide separation of the OTV docking from the space station to prevent accidental collision with manned systems.

Simulations, Chemistry and Physics

Tethers enable independent control of overall accelerations in slowly rotating (<0.07 °/sec) and inertially fixed containers. Accuracy, range, and duration of such controlled gravity depends on the particular engineering embodiments of the tether system. An earth-radial-acceleration of 100 cm/sec^2 is near the approximate upper limit for a gravity grdient system in low earth orbit. Potential applications include, but are not limited to:

- Chambers within which to simulate operations on asteroids, competary nucleii, and moons (Earth's moon is near the upper limit); phobes and demos are within range.
- Chambers or platforms on which to develop and operate manufacturing systems—especially those in which recirculating, debris laden, fluids are produced. This will expedite applications of terrestrial technologies to space.
- Provide another independent and controllable body force which to form large area (generally fragile) structures for use in space, such as optical mirrors, radio reflectors, solar sails, and similar items.

- Provide a macroparticle (dust to golf ban sizes) facility within which collective motions analogous to those in planetary rings (e.g., Saturn), in plasmas, in chemical critical phenomena, and in fluid (including bubbles), and solid-particle flow (dike coal pipelines) can be examined directly on an individual particle basis. A larger range of combinations of body forces could be examined than on earth.
- A laboratory for various experiments in fundamental physics such as: better measurements of G; extended etvos experiments; multipole masses to provide even lower-g levels than free fall.

Each of these applications utilize tethers to provide controllable unidirectional levels of acceleration over long periods of time. Availability of relatively large dedicated volumes equipped with adequate controls (from in-space or Earth personnel) are assumed. Careful attention must be given to stability of the various configurations against random or oscillatory motions of the overall tethered systems over relatively long periods of time (minutes to months).

Tethers provide new opportunities for long term control of accelerations in relatively large volumes over long periods of time at potentially reasonable expense. Very little attention has been given to identifying the interesting possibilities. The five rather disparent topics mentioned likely only hint at the large number of research and applications topics which can be identified. We strongly recommend that a wider ranging identification and definition study be conducted.

Microgravity Requirements

Tether systems provide new types of microgravity (MG) environments that can be used to meet a large variety of user's needs in the fields of life sciences, material sciences, and fluid sciences. A MG environment is characterized by:

- Level (intensity) and direction of residual gravity
- Duration

- Volume
- Quality defined as the persistence of nominal values throughout expected duration.

Classical platforms (drop towers, aircraft, sounding rockets, spacelabs, and space stations) are able to provide:

- Simple point nominal values for intensity and observation of residual gravity
- Direction of residual gravity often unknown
- Time independent or quasi steady nominal values
- Different MG-quality.

Tethered platforms instead offer:

- A continuum of nominal values (intensity, direction)
- Time dimension added
- Controllability of microgravity environments
- Potentially good quality.

The main capabilities made available by TSS are:

- Possibility to cover, with continuity, the range of g levels from microgravity (10^{-5} to 10^{-4}) to 1
- Possibility of varying, in a programmable and controllable manner, the intensity (and probably the direction) of residual gravity.

Typical examples of uses of these added capabilities are:

- Parameteric, g-level (and/or g-direction) investigations (experimental curve vs. experimental point)
- Controllable g-level time profiles to investigate:
  - Frequency-intensity effects
  - G-jitters
  - Hysteresis phenomena
  - Time cycles
  - Intermittency
  - G-noise.

Typical examples in the different fields are:

- Life sciences (determination of threshold g-values for biological processes)

- Material sciences (determination of the level-frequency acceptability regions for crystal growth processes)
- Fluid sciences (g-jitters, contact angle hysteresis, dynamic wetting, spreading, influence of g-history on critical point phenomena, stability enhancing by means of time variation of g-levels)
- Processes (optimization by means of so called g-tuning).

These experiments can be performed in different modes, which include:

- Dedicated missions
- Sold-on experiments
- Get Away Special type experiments
- Multiple tether
- Different mission profiles (including free-flying periods).

Requirements - Operations

Large multifunctional orbiting facilities such as space stations and space platforms impose new operational requirements. Such facilities will be composed of various functional elements. These may include, for example, transfer vehicle docking and maintenance equipment, laboratories, and sensor packages. Potential benefits are anticipated from the separation of some of these elements from the main structure. The major benefit is isolation from contamination or interference by other elements.

Additionaly, hazardous or contaminating operations such as transfer vehicle docking may beneficially be remotely conducted. Taking advantage of the multifunctional facility implies that each separated element is occasionally brought to the main structure for services. Such services are maintenance, resupply, changeout, and storage.

One functional requirement, therefore, is for selected functional element deployment stationkeeping and retrieval relative to a main structure. As examples:

- Antenna farms removed from interference by the main structure

- Sensor packages kept clear of transfer vehicle contamination operation
- Teleoperator retrieval of a passive transfer vehicle and return to a space station
- Microgravity research and operations facilities in proximity to and tended by a space station.

III. MEANS FOR ACHIEVING ARTIFICIAL GRAVITY

The following table summarizes the requirements for artificial gravity.

- MEDICAL: VARIABLE GRAVITY FACILITY ($>10^{-3}$)
- TECHNOLOGY: MANNED R&D FACILITY
- MICROGRAVITY: VARIABLE GRAVITY FACILITY ($<10^{-3}$)
- HABITABILITY: ROTATING SYSTEM (>0.10 G'S)
- OPERATIONS: TANK FARM
  ANTENNA/SENSOR FARM
  TMS/OTV RETRIEVAL

The means for developing these artificial gravity capabilities are discussed in the following six subsections.

1 - Manned Artificial Gravity Laboratory

Background. Technology developments (high strength plastics) and an improved understanding of orbital dynamics have offered two new options in space flight. First, the use of tethers deployed in a gravity gradient orientation allows finely controlled experimentation in microgravity sciences. This not only includes the ability to hold accurately predetermined levels of microgravity for indefinite periods, but also the capability to vary these levels along arbitrary time profiles—again for extended durations. Secondly, tethers also reopen the question of the use of artificial gravity to improve habitability, increase productivity, and reduce subsystem design/development problems in manned space stations. Past studies discounted such concepts since it was found that, within practical limitations of rigid structures, rotation rates for reasonable "g" levels would actually induce rather than suppress. Motion sickness and that coriollis forces, tethers with large artificial gravity gradients, might actually degrade habitability/productivity below levels achieved in zero-g. But gravity gradient tethers would eliminate these effects while producing useful levels of artificial gravity and much shorter whirling tethers could be employed to produce even higher values of acceleration at rotation rates low enough to result in an acceptable environment.

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It is noted that testing of habitability/productivity factors, as well as development of many medical/physiological experiments is best pursued when the human subjects are engaged in normal, everyday tasks. Thus useful synergism can be developed in a manned laboratory where medical, physiological habitability and productivity artificial gravity experiments are conducted while the subjects of these tests are engaged in a program of microgravity science and technology experiments. The advantage of a manned laboratory are summarized in Fig. 13.

- SIMULTANEOUSLY UNDERTAKES A RANGE OF ARTIFICIAL GRAVITY EXPERIMENTAL WORK
  - MEDICAL/PHYSIOLOGICAL
  - TECHNOLOGY EXPERIMENTS
  - MICROGRAVITY SCIENCES
    - LIFE SCIENCES
    - MATERIAL SCIENCES
    - FLUID SCIENCES
  - HABITABILITY/PRODUCTIVITY
- OPERATES IN EITHER A GRAVITY GRADIENT OR LONG RADIUS WHRIL MODE
  - SAME TETHER EQUIPMENT
- DOUBLES AS GENERAL PURPOSE LABORATORY AND IT'S NECESSARY LIFE SUPPORT AND CREW SYSTEMS ARE AN INTEGRAL PART OF THE CORE SPACE STATION DESIGN

Figure 13. Manned Artificial Gravity Laboratory (MAGL)

Laboratory Description. The Manned Artificial Gravity Laboratory (MAGL) consists of a 14-ft diameter module approximately 40-ft long. It contains crew systems for its two-man crew and the necessary life support and environmental control systems. Communications systems would be minimal since, in remote operations, it would only communicate with the core station (perhaps hardwire) and data would be stored on-board return that transmitted. Since the lab would never require more than a few hours to reattach itself to the core station, the necessary systems need not be redundant though emergency life support (possibly spacesuits) would be available. Similarly, these systems need not be additions to those normally required by the station since the crew quarters would be those normally occupied when the module was attached to the core and other systems would supply the redundancy and backups required in all critical subsystems. Additionally, electrical energy source would not be necessary within the module since, in whirling tether operations, it would receive its power via hardwire from the core (~1000 ft); and in the gravity gradient tether mode, it would receive power from the tether itself (electrodynamic). If the electrodynamic tether concept proves impractical, the MAGL could use its own relatively small solar cell power system while operating in the gravity gradient tether mode. But again, this could be part of the total station power supply with additional safety resulting from the fact that there was an isolated redundant total system (array, regulations, batteries). The MAGL would also have its own RCS propulsion since this would be required to establish the whirl mode and greatly facilitate deployment and redocking. But again, this can be part of the total station's redundant systems since the deployed MAGL could be docked by use of either the core or MAGL RCS while the other was inactive. Much of the laboratory equipment would be basic instrumentation, data gathering, and facility items found in descriptions of General Purpose Laboratories as described in previous space station studies (see 69-71 and B reports). Thus the MAGL can serve as the GPS when docked to the core.

For the reasons discussed here, cost of a station within a MAGL integrated into its original design should be much less than if it were a later addition. In fact, the integrated MAGL offers an exception increase in stations capability to undertake useful science and technology efforts for a very modest increase in total costs.

MAGL Operations (Fig. 14). Since the MAGL has its own RCS/propulsion system, initial deployment and terminal docking would be as a free flying module. Though the tether would be attached, no tension would be applied by the tether reel system. This greatly simplifies tether system design, since gravity gradient forces are very small at small separations. In the gravity gradient mode, the RCS would only be used to damp unwanted dynamic motions when separation distances were more than several hundred meters. In the whirl mode, RCS propulsion would accomplish the entire deployment sequence, including establishing the whirl velocity (~30 to 60 fps). From a space system design viewpoint, it would be much easier to allow the core station to also rotate in this mode. While other work schedules would undoubtedly be interrupted, many medical and habitability objectives could be achieved in a short period since investigation of long duration would be limited to gravity gradient deployments.

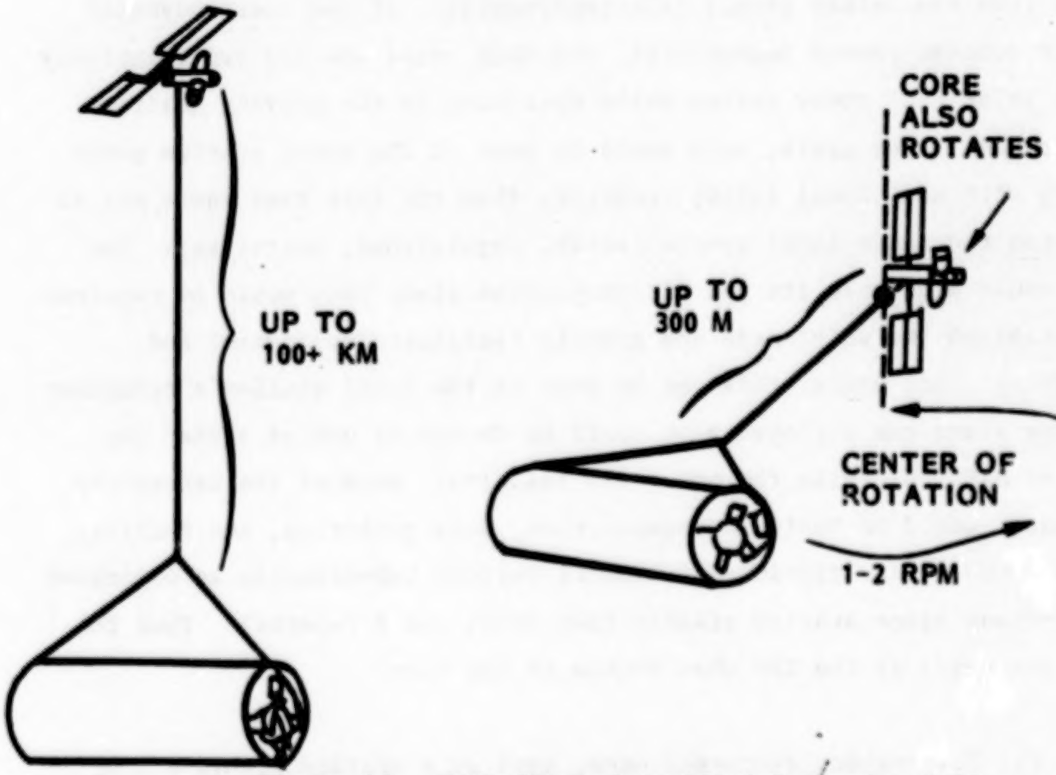


Figure 14. MAGL (Manned Artificial Gravity Lab)

2 - Use of Tethered Capsule as Very Low-G Facility

In low earth orbit, space vehicles experience a deceleration due to drag of 10^{-6} or more. Some experiments and/or processes may require a lower-g environment.

A very low-g facility is proposed. The low-g capsule follows the Shuttle (or other host spacecraft) on a tether. The tether will be reeled in to maintain a force on the capsule that just offsets drag, thereby maintaining the capsule at near zero-g.

The rate of reel-in velocity will vary with time according to:

$$v = a\,t$$

where a = deceleration of the Shuttle due to drag (and force on the tether)

t = time from beginning of the low-g period

Similarly, the initial length of the tether would be:

$$L = 1/2\,a\,t^2$$

If the drag is 10^{-6} g, then the tether would be 25 miles long to achieve a 24 hr low-g period. The reel-in velocity would be about 2.5 ft/sec at the end of the period.

The boom to direct the force along the orbital path of the capsule would be several hundred feet long (400 ft for the example given), and it would have to be retracted as the capsule moves closer to maintain the force vector on the capsule to be just opposite the drag vector.

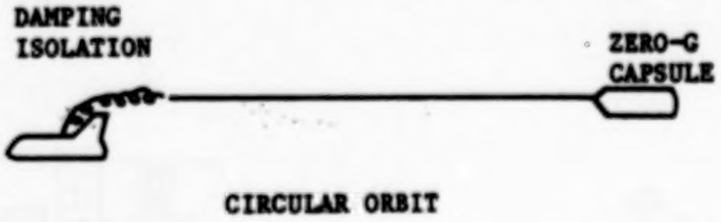
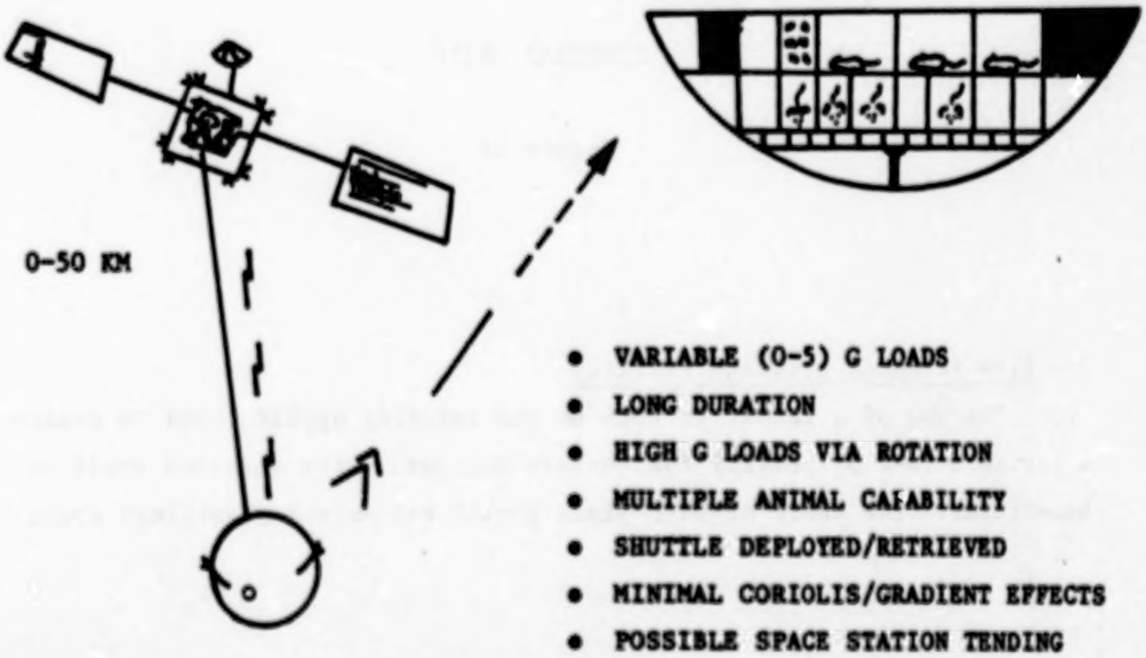


Figure 15

3 - Life Sciences Research Facility

The use of a tether in both GG and rotating applications to create a variable (0-1 G) gravity for researching basic life sciences would be beneficial. The study of both plant growth and animal physiology would greatly increase our knowledge of the effects of gravity on all life forms. This would, in turn, support studies on the need for AG on a permanent manned space station.

It is not practical to perform long duration (>1 month) life sciences (especially animal) experiments without manned tending. (The complexity of tasks, unknowns involved, and adverse results of a system failure or death of an on-board animal, makes periodic manned servicing mandatory.) This could be accomplished using a shuttle in several ways. First, a one week mission could gain a limited amount of valuable initial data. An extended duration shuttle (<21 days) would provide additional valuable data. Another alternative is to deploy the tether system, allow it to operate independently for up to a month and retrieve the system on a later flight (Fig. 17). A final alternative which is attractive is to use a space station for long duration manned tending (Fig. 18). It should be noted in all of these cases, that the tending need not be at the tethered facility. It can occur between experiments after retracting the tether system.



- VARIABLE (0-5) G LOADS
- LONG DURATION
- HIGH G LOADS VIA ROTATION
- MULTIPLE ANIMAL CAPABILITY
- SHUTTLE DEPLOYED/RETRIEVED
- MINIMAL CORIOLIS/GRADIENT EFFECTS
- POSSIBLE SPACE STATION TENDING

Figure 17. Artificial Gravity Life Sciences Research Tether-Sat

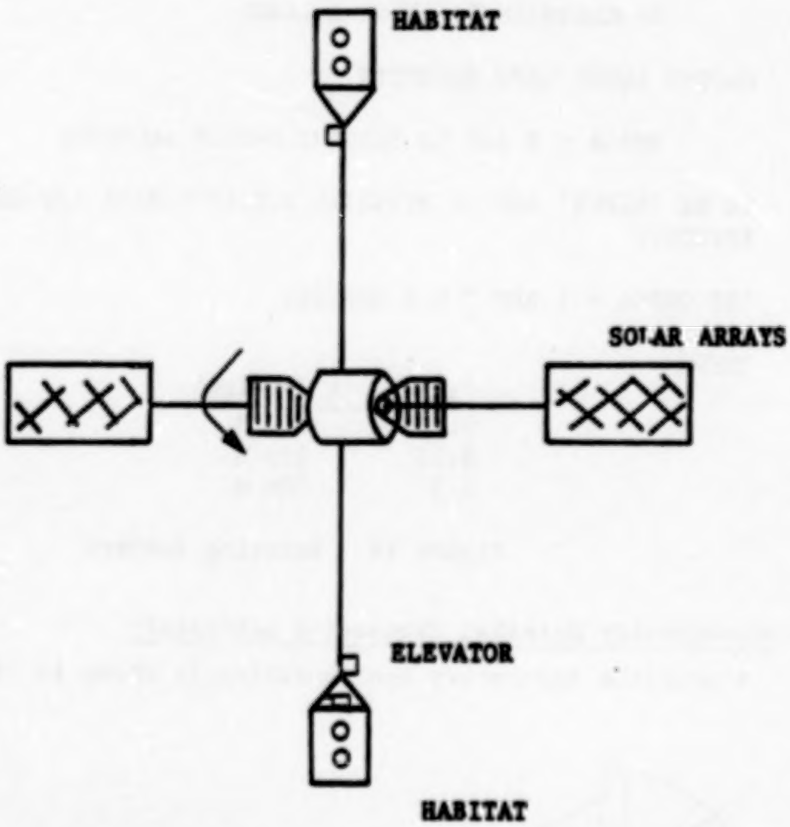


Figure 18. Medical/Physiological Countermeasure Artificial Gravity Space Station Design

The tether system competes with smaller centrifuge concepts for many of these experiments. There is, however, a significant advantage to the tether concept. The extremely long lengths achievable with a tether (100's of meters-kilometers) minimizes both coriolis accelerations and gravity gradient effects present in small centrifuges (Fig. 19). The problems associated with a rotating tether facility, however, need to be studied further.

$g = OMEGA^2 R$

TO MINIMIZE CORIOLIS WANT R LARGE
TO MINIMIZE GRAVITY GRADIENT WANT R LARGE

TO MAXIMIZE "g" WANT R LARGE

GROUND BASED DATA SUGGESTS

OMEGA $\leq$ 3 RPM TO PREVENT MOTION SICKNESS

TO BE "SAFER" AND TO MINIMIZE ROTATION RATE AND CORIOLIS EFFECTS:

LET OMEGA = 1 RPM $\simeq$ 0.1 RAD/SEC

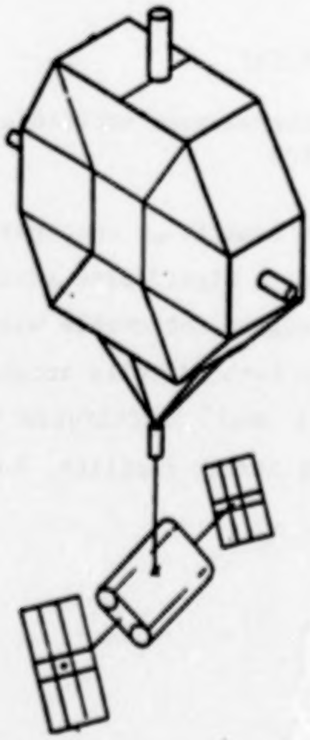
THEN

"g"	R (RADIUS)
0.1	100 M
0.25	250 M
0.5	500 M

Figure 19. Rotating Tethers

4 - Micrograviity Material Processing Laboratory

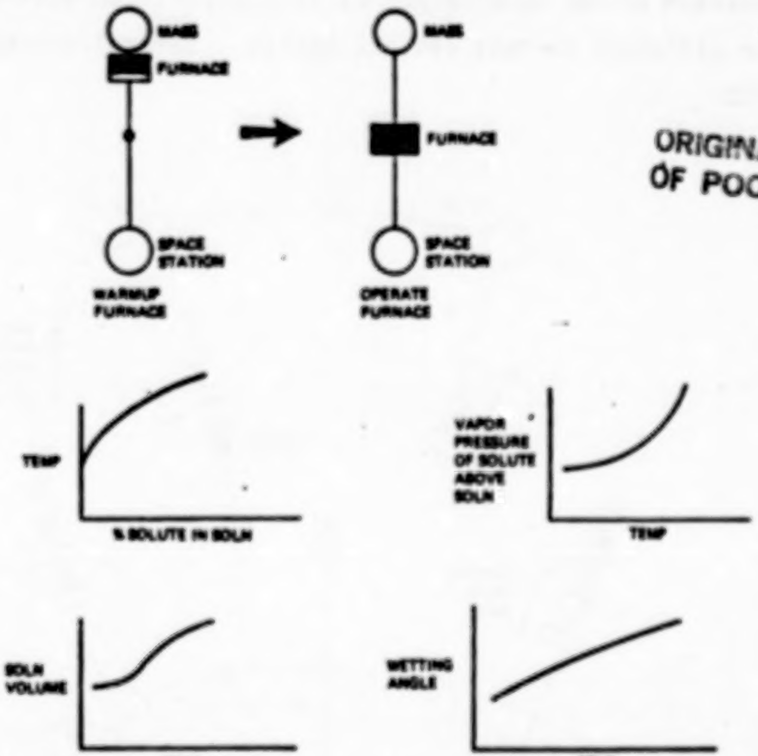
A possible laboratory configuration is shown in Fig. 20.



- MODULAR
  - SHUTTLE LAUNCHED
- SERVICEABLE
  - CONTROLLED FROM SPACE STATION
  - INSERT RAW MATERIALS CARTRIDGES
  - REMOVE PROCESSED CARTRIDGES
  - OCCASIONALLY REFURBISHED AT SPACE STATION
- VARIABLE G (CHANGE TETHER LENGTH)
  - LOW G MELT WITH ZERO G SOLIDIFICATION
  - LOW G MELT WITH VARIABLE G SOLIDIFICATION
- ORBIT DECAY PROVIDES ELECTRICAL POWER

Figure 20. Microgravity Materials Processing

Many properties of fluids vary with temperature (see Fig. 21 for examples). Since the temperature of materials must be elevated substantially above the ambient in many materials processing in space (MPS) applications, these temperature dependent property variations may cause inhomogeneities in the fluid. These inhomogeneities may defeat the purpose of microgravity growth (i.e., "perfect" materials). If the material is heated at the end of a tether, the gravity gradient force may be used to "clean" the inhomogeneities from the fluid. The system may then be moved to the cg where uniform growth in a minimum g environment may be performed.


MASS
FURNACE
SPACE STATION
WARMUP FURNACE
MASS
FURNACE
SPACE STATION
OPERATE FURNACE
TEMP
% SOLUTE IN SOLN
VAPOR PRESSURE OF SOLUTE ABOVE SOLN
TEMP
SOLN VOLUME
TEMP
WETTING ANGLE
TEMP

ORIGINAL PAGE IS
OF POOR QUALITY

Figure 21

5 - Tethered Tank Farms

To support the operation of OTVs from a space station, it has been proposed that storage tanks for propellants be located at some distance from the station by means of a gravity gradient tether. Two reasons have been cited for this concept:

- Existence of "artificial gravity" would facilitate transfer of fluids
- Safety of the manned station would be enhanced by the remote location of hazardous liquids.

In operation, such a concept would require the shuttle to dock/berth at the remote location to deliver the propellants and the usually unmanned OTV to berth at the same point to receive propellants.

Locations of fluid storage tankage remote from a space station by tethering will provide settling of liquid. Settling will eliminate or simplify liquid acquisition device requirements. For cryogens, elimination of the uncertainty of liquid position will permit designs of a more efficient thermal central system. Several concepts are shown in Fig. 22.

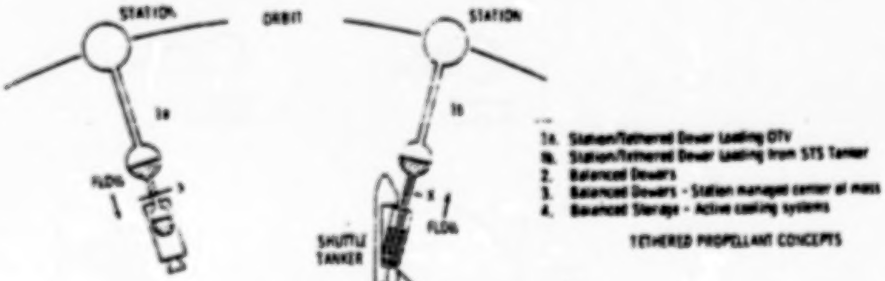

STATION
ORBIT
STATION
1a
1b
FLOW
X
X
FLOW
SHUTTLE TANKER
1a. Station/Tethered Dewar Loading OTV
1b. Station/Tethered Dewar Loading from STS Tanker
2. Balanced Dewars
3. Balanced Dewars - Station managed center of mass
4. Balanced Storage - Active cooling systems
TETHERED PROPELLANT CONCEPTS
X
Continuous Cooling Cycle
X
X
ORBIT
ORBIT
STATION
2
4
3
Continuous Cooling Cycle
X
X
X

Figure 22

A major problem in resupply of liquids to a space station is removal of non-condensible pressurant prior to refill. An option is the use of autogenous pressurization, but a better solution will be the use of tethering to settle liquid away from the vent port, so that the ullage can be directly vented. Once the non-condensible gas has been removed, resupply can be accomplished by a "no-vent" fill procedure. It is unlikely that tether technology will permit refill with direct venting (rather than no-vent fill), because the kinetic energy of transfer will result in large liquid motions, the likelihood of venting liquid. Thus "artificial gravity," offered by the remote gravity gradient location, could significantly simplify the hardware (propellant retention and zero-g vent devices). In addition, it may also offer gravity feed of propellants from one tank to another. While this latter system would be a rather slow system (within practical limitations), it reduces pressurization requirements, and because of the slow transfer rates, reduced dynamic interactions. It is also noted that "artificial gravity" would greatly reduce the problem of measuring liquid quantity within a tank.

Examination of the storage problem indicates that quite low levels of acceleration will allow the liquid transfer tactics outlined above. Bond numbers of ten can be achieved for all propellants of correct interest at 10^{-5} g's and this is believed sufficient to allow pressurized transfer at useful rates. Hence tank location at little more than 100 ft from the station/tank system center of gravity will suffice (Fig. 23).

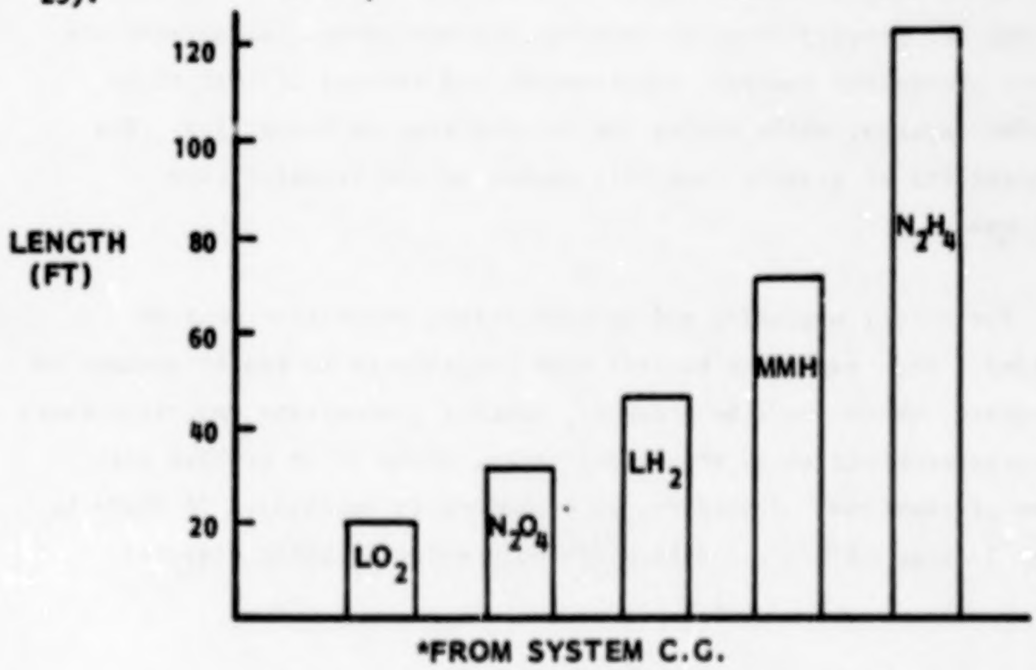


Figure 23. Tether Length* (Bond No. = 10)

The safety advantages divide into two categories:

- Physical separation reduces possible hazards due to either explosive rupture of the tankage or leakage
- Remote docking/berthing of the orbiter and unmanned OTVs reduces the possibility of catastrophic collision.

Means of Achieving Fluid Storage and Transfer. A tether system for storing and transferring liquid with a bond number of 10 would allow the surface tension forces to be overcome to settle the fluids, allow only vapor to be vented in a tank being filled, and allow residual during transfer to be minimized by minimizing tank cavitation. This bond number corresponds to between 20 and 120 ft tether length from the center of gravity for the various propellants. For these short tether lengths, booms may be preferrable. Longer tether lengths would be needed to reduce sloshing and to provide for gravity feed fluid transfer. The sloshing displacement, important for determining if fluid will uncover the outlet, will be reduced by longer tether length, which means greater gravity, by converting the kinetic energy resulting from a disturbance into potential energy in a shorter distance. Gravity feed will use the gravity force to overcome transfer drag. Advantages are reduced pressurant resupply requirements and reduced initial fluid transfer impulse, while having the disadvantage of being slow. The applicability of gravity feed will depend on the transfer time requirement.

For safety explosion and contamination, separation must be provided. Most explosion hazards with propellants is due to leakage to atmosphere, which won't be present. Another predominate explosion cause is overpressurization of propellant tanks, which is no problem with proper precautions. Therefore, an explosion is unlikely. If there is enough leakage to cause a contamination problem is being disputed.

In evaluating the desirability of remote/gravity gradient location of a tank farm, it must be pointed out that this concept only represents an alternative method of accomplishing propellant transfer in space or positive displacement tankage is one obvious solution to zero-g transfer of liquids. However, this is both heavy and unreliable where repeated usage is involved. But the technology of both passive liquid retention and active vent systems for transfer in zero gravity is fairly well advanced. In fact, expulsion of storable propellants with use of light weight passive retention screens has been well demonstrated by the orbiter OMS tankage. Thus, the choice involves a value judgment between two competing systems.

Where the safety issue is concerned, it is believed that storage safety is generally improved by the vacuum/zero-g environment when compared to storage problems on earth. Since, to pursue space flight in any form, we must work in close proximity to propellant storage tanks on earth, it is difficult to believe that storage safety is a significiant issue on orbit--at least on a rotative sense.

Berthing/docking safety is a significant problem, particularly if OTVs are frequently launched from the space station. But remote docking involves considerable additional complexity operationally. First of all, typically the orbiter will deliver both propellants and other space station supplies. Thus, either two dockings or transfer of materials and personnel between the station and remote tank farm are required. Similarly, the returned OTV must not only be filled with propellants, its payload must either be changed or installed. Additionally, OTV maintenance must be at least occasionally performed. Thus, the remote tank farm could conceivably, through the additional required operations, be counter productive where safety is concerned.

It must also be noted that, for the distances required by both safety and propellant transfer criteria, rigid deployable booms are an obvious alternative to tethers. In fact, the relative ease with which they may be deployed and retracted may make them more desirable than tethers in this application.

For reasons discussed above, it is concluded that:

- Remote storage of propellants at a space station offers an alternative operational scheme with some noted advantages where propellant transfer is concerned as well as some safety and contamination advantages. However, it is thus worthy of future study since it is not a clear choice over storage in close proximity to the station.

6 - **Operation Modes**

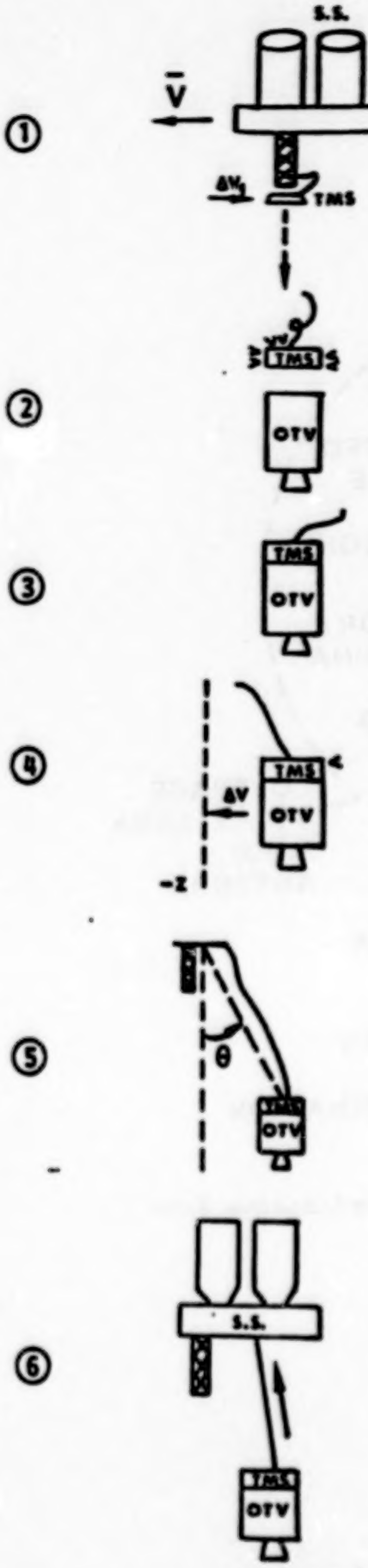
Separation of functional elements from the main structure may be accomplished by:

Booms
Free Flyers
Tethers.

Of the three, tethers give the best combination of operational simplicity and flexibility. Tethered platforms do not require autonomous stationkeeping subsystems as free flyers do (although they do require autonomous altitude stabilization). Maintenance or resupply of a tethered subsystem is simplified by the capability of "reeling in" the platform to the main structure.

The physical link may possibly provide communications to the tethered platform, perhaps with a fiberoptic cable that does not bear the stress. In addition, power may be transferred from the main structure, if adverse interactions with the ambient plasma can be avoided. Both these possibilities deserve further study.

Figures 24 and 25 illustrate two tethered operations concepts. Figure 24 shows the retrieval of a transfer vehicle in the larger vicinity of a space station. Figure 25 illustrates the advantages of an antenna/sensor farm. The increased antenna coverage and the removal of sensors from contaminating operations are depicted.


S.S.
$\bar{V}$
ΔV_1
TMS
TMS
OTV
TMS
OTV
ΔV
TMS
OTV
-Z
θ
TMS
OTV
S.S.
TMS
OTV

① TMS BURN IN THE -V DIRECTION CAUSES TMS TO MOVE IN -Z DIRECTION REL TO S.S.

② TMS, WITH SLACK TETHER IS GUIDED TO OTV

③ TMS MATES WITH OTV

④ TMS MANEUVERS OTV TOWARDS THE -Z LINE (L.V.) EXTENDING FROM THE S.S.

⑤ WHEN θ < (TBD), TMS JET ACTIVITY CEASES. TETHER IS TAUTENED

⑥ USING ACTIVE CONTROL FOR LIBRATION DAMPING, THE TETHER CONTROLLER REELS IN THE TMS-OTV PAYLOAD

Figure 24. OTV Retrieval with Tethered TMS

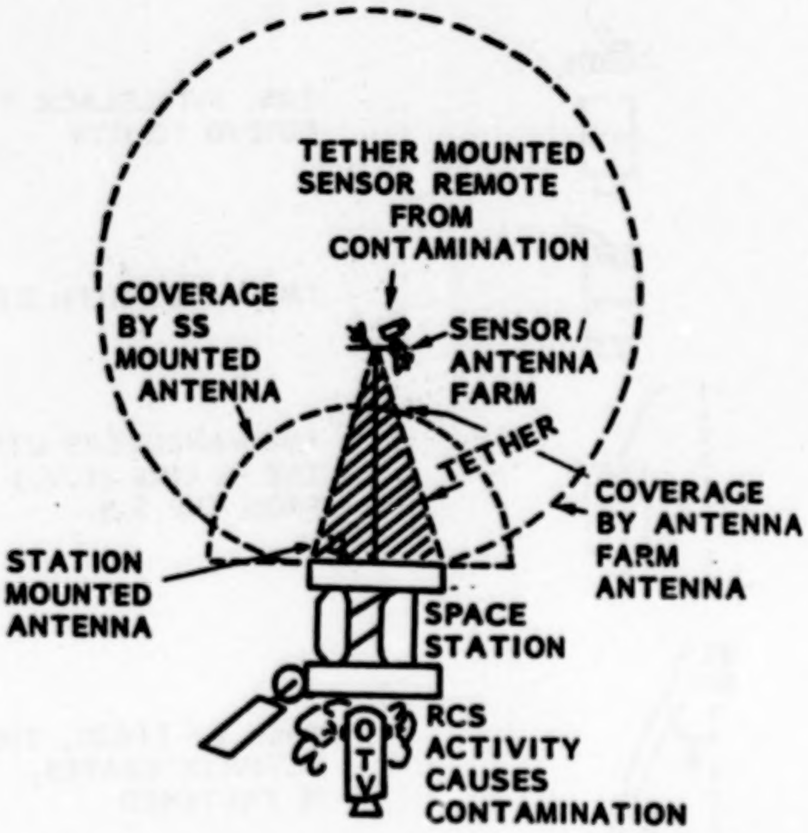

TETHER MOUNTED SENSOR REMOTE FROM CONTAMINATION
COVERAGE BY SS MOUNTED ANTENNA
SENSOR/ ANTENNA FARM
TETHER
COVERAGE BY ANTENNA FARM ANTENNA
STATION MOUNTED ANTENNA
SPACE STATION
OTV
RCS ACTIVITY CAUSES CONTAMINATION

Figure 25. Tether- Mounted Sensor/Antenna Farm

IV. PRESENTATIONS MADE TO THE PANEL

1 - OVERVIEW - R. Freitag

Problem

The name of the game--how do you use it?
Question: Are there any requirements for artificial gravity (aboard a space station)? How much? How do you get it? How do you use it?

WE NEED A RIGOROUS REQUIREMENTS ANALYSIS; WE WILL LOOK INTO IT

Needs

In Ivan's keynote, in the charge to the us, there are two main aspects--INTUITIVE

(1) MEDICAL - LIFE SCIENCES/HABITABILITY
(2) TECHNICAL - FLOWING FLUIDS, MIXING, WETTING, COOLING, ETC.
(3) TECHNOLOGY

Approach

Space Station - Normal tether for S&A
No missions yet
Will baseline facilities

For systems aspects - Not baselined-artificial gravity
Space station conventional
  -- industry not up to spec
  -- Need results
Iterations before hardware
Interactions of concept analysis

1 year	- Requirements
15 May	- Scope
15 Jul	- Budget
15 Dec	- Start Bid Specs
15 Oct 84	- Start Detail Definition
15 Oct 86	- Cut Hardware

Plenty of time to input.
User Friendly - We mean it.

Open-Ended - Evolutionary (Capability/Technology)

- Not preclude growth
- Certainly use tether technology, general tool
  - Mission needs
  - Stowage
  - Capture
  - Growth
- On-orbit test bed
  - Medical
  - Technical

Approach

- Requirements Analysis
- Technology Stimulation

N85-20366

2 - PHYSIOLOGICAL CONSIDERATIONS OF ARTIFICIAL GRAVITY

D. B. Cramer

ARTIFICIAL GRAVITY – WHY MIGHT WE NEED IT?

- WEIGHTLESSNESS PRODUCES SIGNIFICANT PHYSIOLOGICAL CHANGES:
  - THE MECHANISMS ARE NOT WELL UNDERSTOOD
  - WHETHER THESE CHANGES WILL STABILIZE OR PROGRESS TO PATHOLOGICAL STATES IS NOT KNOWN
  - WITH CURRENT COUNTERMEASURES, WE ARE PROBABLY SAFE TO SIX MONTHS' EXPOSURE
  - THE POINT AT WHICH RAPID READAPTATION TO EARTH GRAVITY BECOMES COMPROMISED IS PRESENTLY UNKNOWN
  - THERE IS MUCH WE NEED TO LEARN
  - A SPACE STATION IS THE IDEAL LABORATORY FOR STUDYING THE PHYSIOLOGICAL EFFECTS OF WEIGHTLESSNESS
- AS OUR CURRENT COUNTERMEASURES CONSUME AN EVER INCREASING PORTION OF AVAILABLE CREW TIME, MORE EFFICIENT ALTERNATIVES BECOME NECESSARY
- ARTIFICIAL GRAVITY IS THE MOST "NATURAL" COUNTERMEASURE

ARTIFICIAL GRAVITY – PHYSIOLOGICAL ISSUES

- GENERIC ISSUES:
  - ACUTE EFFECTS
  - NEW SET POINTS IN WEIGHTLESSNESS
  - STABILIZED STATE ALOFT
  - CAPACITY FOR RAPID READAPTATION TO EARTH GRAVITY
  - ROLE OF WEIGHTLESSNESS IN THE DEVELOPING INDIVIDUAL
  - EFFECTS OF ARTIFICIAL GRAVITY–HOW MUCH? HOW LONG?
- THREE ORGAN SYSTEMS ARE KNOWN TO BE GRAVITY SENSITIVE:
  - CARDIOVASCULAR
  - SKELETAL
  - VESTIBULAR

ARTIFICIAL GRAVITY—AFFECTED SYSTEMS

- CARDIOVASCULAR:
  - ORTHOSTATIC GRADIENTS
  - ACUTE FLUID SHIFTS
  - ORTHOSTATIC INTOLERANCE
  - COUNTERMEASURES:
    - "G" SUITS
    - LOWER BODY NEGATIVE PRESSURE
    - SALT LOADING/DRUGS
  - EARLY DEVELOPMENT
- SKELETAL:
  - PERSISTENT LOSS
  - LOAD BEARING BONES
  - IRREVERSIBILITY
  - COUNTERMEASURES:
    - SKELETAL LOADING
    - DRUGS
  - EARLY DEVELOPMENT
- VESTIBULAR:
  - SPACE SICKNESS
  - ILLUSIONS
  - COUNTERMEASURES:
    - DRUGS
    - ADAPTATION
    - BIOFEEDBACK
  - EARLY DEVELOPMENT

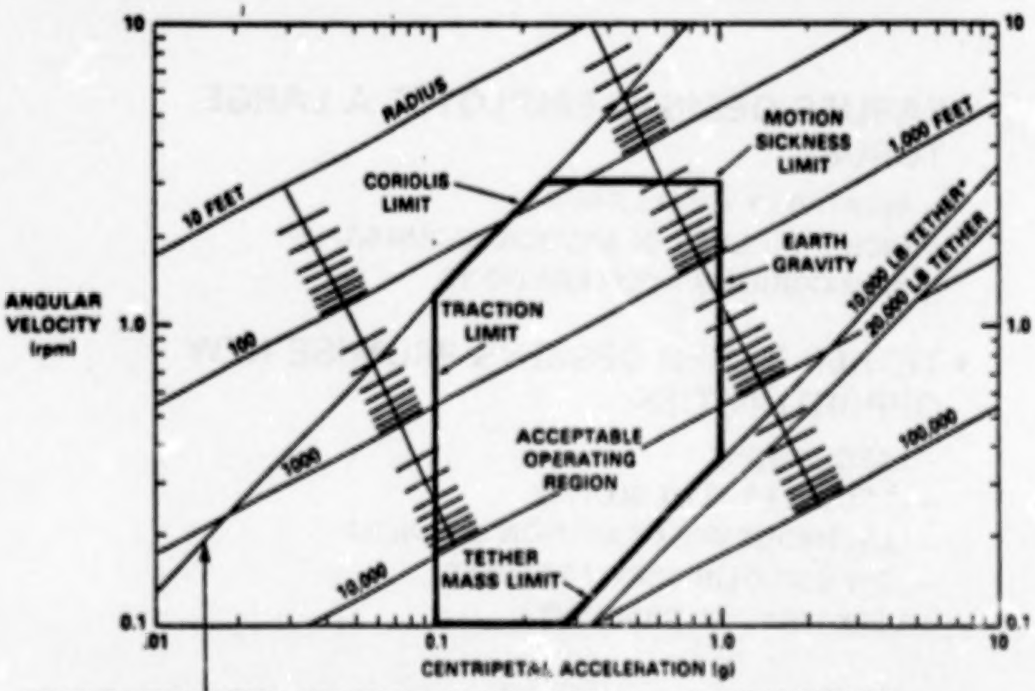
ARTIFICIAL GRAVITY — OPTIONS

- EARLIER DESIGNS EMPLOYED A LARGE TORUS:
  - RELATIVELY SMALL RADII
  - HIGH INCIDENCE OF MOTION SICKNESS
  - HIGH CORIOLIS ACCELERATIONS
- TETHER-BASED DESIGNS PROMISE NEW OPPORTUNITIES:
  - LARGE RADII
  - IT ROTATES—BUT SLOWLY
  - LOW INCIDENCE OF MOTION SICKNESS
  - LOW CORIOLIS ACCELERATIONS
  - VERY LOW "G" GRADIENTS

ARTIFICIAL GRAVITY— PARAMETERS

- UNAIDED TRACTION REQUIRES 0.1 G
- ANGULAR VELOCITY SHOULD BE LESS THAN 3.0 RPM TO AVOID MOTION SICKNESS
- MAXIMAL CENTRIPETAL ACCELERATION NEED NOT EXCEED EARTH GRAVITY
- CORIOLIS ACCELERATION SHOULD NOT EXCEED 0.25 CENTRIPETAL ACCELERATION FOR A LINEAR VELOCITY OF 3 FEET/SECOND IN A RADIAL DIRECTION
- "G" GRADIENT SHOULD NOT EXCEED 0.01 G/FOOT IN RADIAL DIRECTION
- TETHER MASS MIGHT BE LIMITED TO 10,000 TO 20,000 POUNDS

ARTIFICIAL GRAVITY PARAMETERS



CORIOLIS ACCELERATION = 0.25 CENTRIPETAL ACCELERATION FOR 3 FT. SEC^{-1} RADIAL VELOCITY

* TETHER MASS LIMIT: 100,000 LB MODULE AT EACH END. KEVLAR, CYLINDRICAL TETHER

ARTIFICIAL GRAVITY— STUDY APPROACH

GROUND-BASED LABORATORY

- SIMULATED WEIGHTLESS EXPOSURE
  - BED REST
  - WATER IMMERSION
- RECONDITIONING STIMULI
  - INCLINED PLANE
  - CENTRIFUGE
  - ALTERNATIVE COUNTERMEASURES

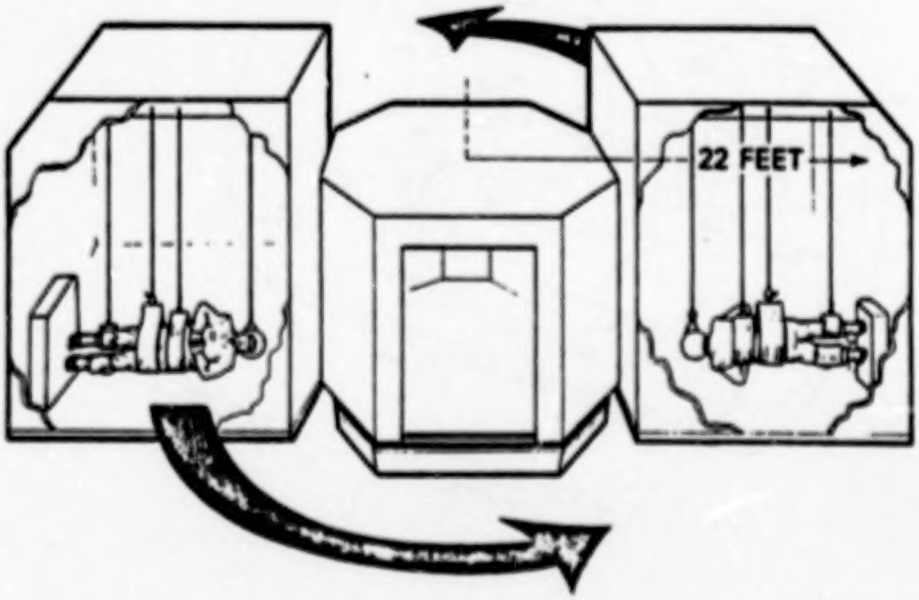
STS SPACELAB

- ACUTE EFFECTS OF WEIGHTLESSNESS
- VALIDATE ANIMAL MODELS
- IMPROVE CURRENT COUNTERMEASURES

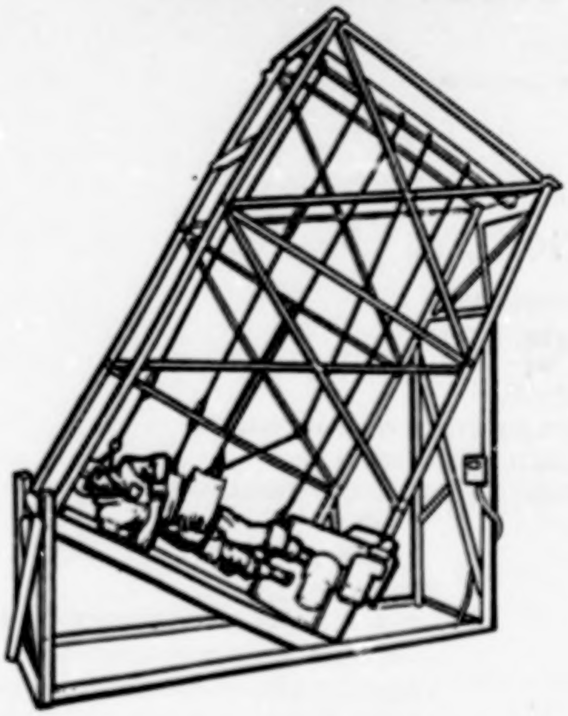
SPACE STATION

- CHRONIC EFFECTS OF WEIGHTLESSNESS (ANIMALS)
- VALIDATE MODELS IN HUMANS
- DEVELOP SECOND GENERATION COUNTERMEASURES
- BASIC RESEARCH IN GRAVITATIONAL BIOLOGY

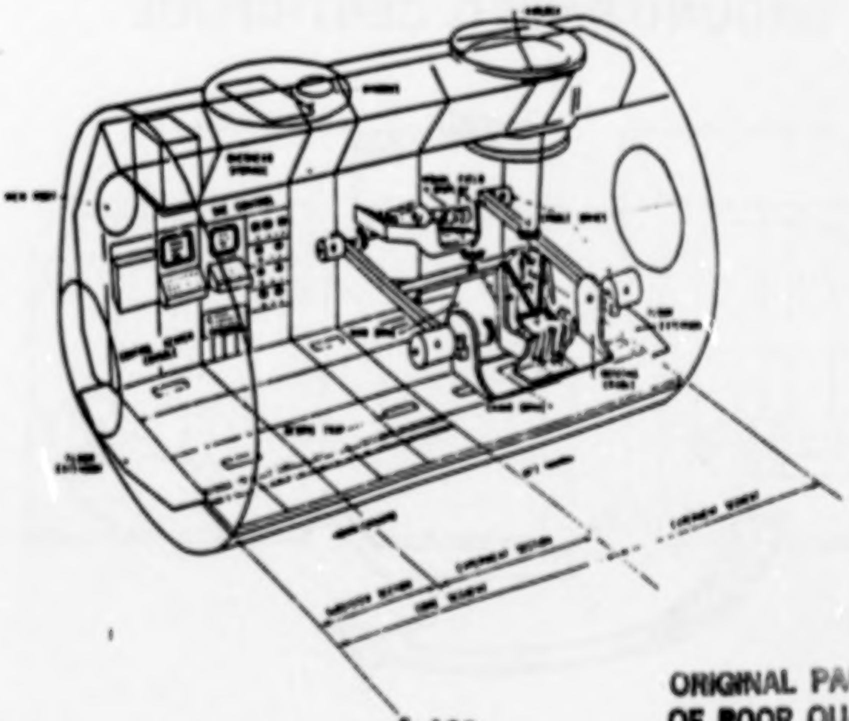
ARTIFICIAL GRAVITY — GROUND-BASED CENTRIFUGE



ARTIFICIAL GRAVITY – INCLINED PLANE



ARTIFICIAL GRAVITY– SPACE-BASED CENTRIFUGE



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ARTIFICIAL GRAVITY—SUMMARY

- WEIGHTLESSNESS PRODUCES SIGNIFICANT PHYSIOLOGICAL CHANGES
- WHETHER THESE CHANGES WILL STABILIZE OR ACHIEVE MEDICAL SIGNIFICANCE IS NOT YET CLEAR
- ARTIFICIAL GRAVITY IS THE MOST PHYSIOLOGICAL COUNTERMEASURE
- TETHER SYSTEMS REPRESENT AN ATTRACTIVE APPROACH TO ARTIFICIAL GRAVITY
- MUCH MORE RESEARCH IS NECESSARY TO EVALUATE THE NEED FOR ARTIFICIAL GRAVITY

3 - TECHNOLOGY APPLICATIONS

T. Taylor

ARTIFICAL GRAVITY

- TORUS
- BIOLOGICAL ASPECTS
- CENTRIFUGAL FORCES
- ROTATIONAL FACITITY
- SEPARATION SCIENCES
- CONCLUSIONS

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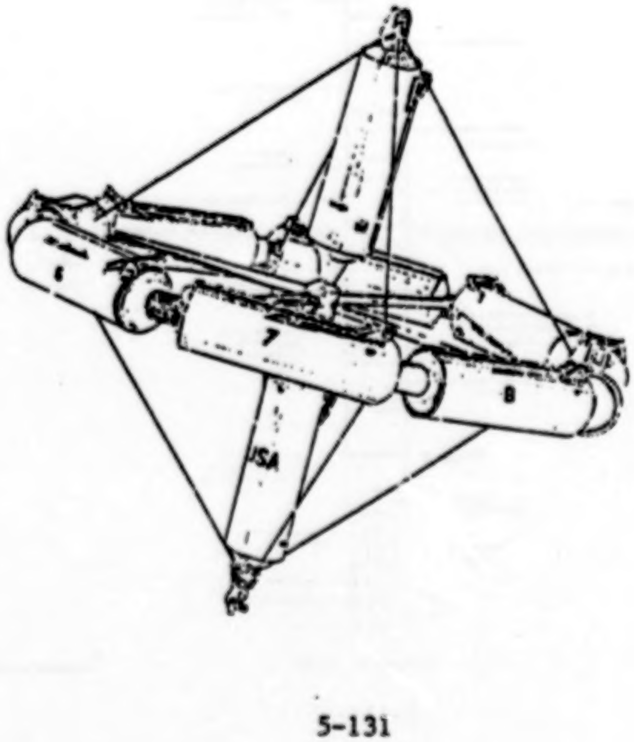

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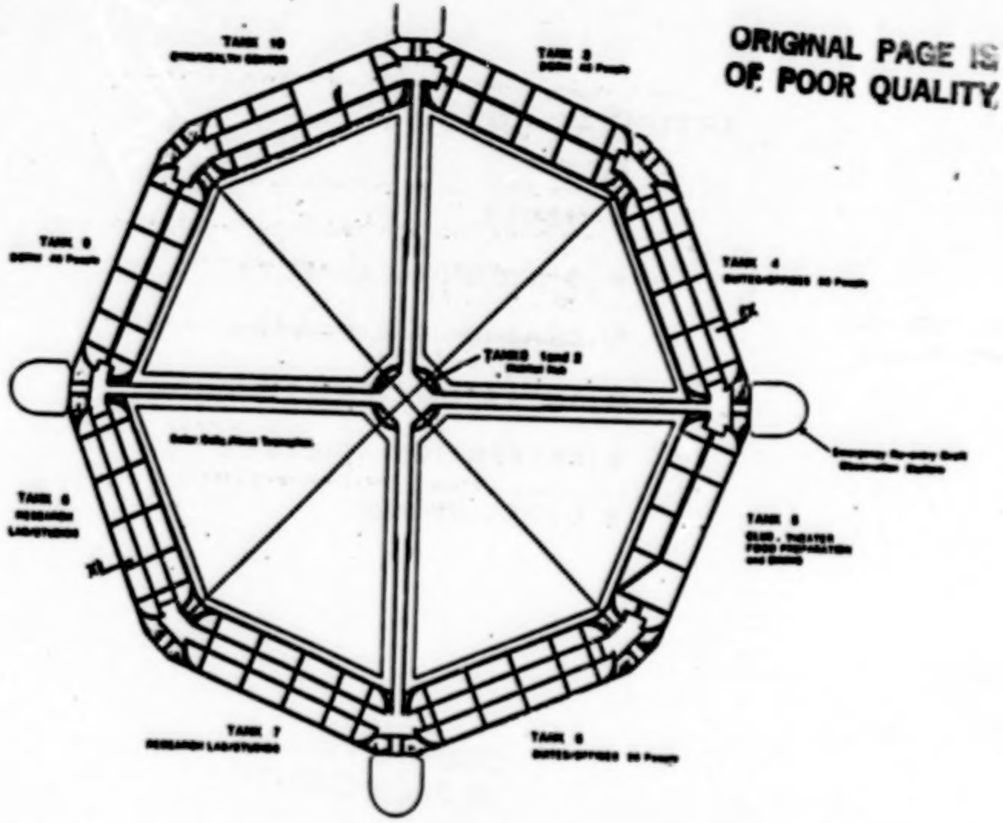
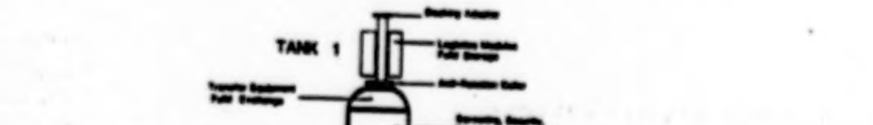

TANK 10
TANK 3
TANK 9
TANK 4
TANKS 1 and 2
TANK 8
RESEARCH
LAB/STUDIOS
TANK 5
CLUB, THEATER
FOOD PREPARATION
and DINING
TANK 7
RESEARCH LAB/STUDIOS
TANK 6

HABITAT MASTER PLAN


TANK 1
TANK 2
SECTION X

HABITAT MIR

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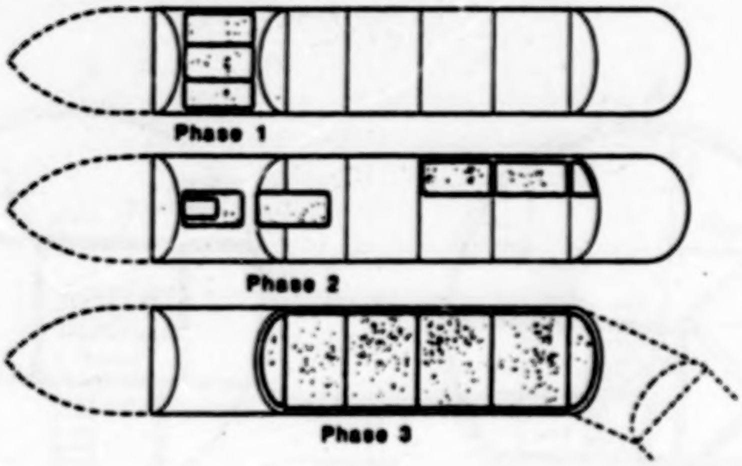
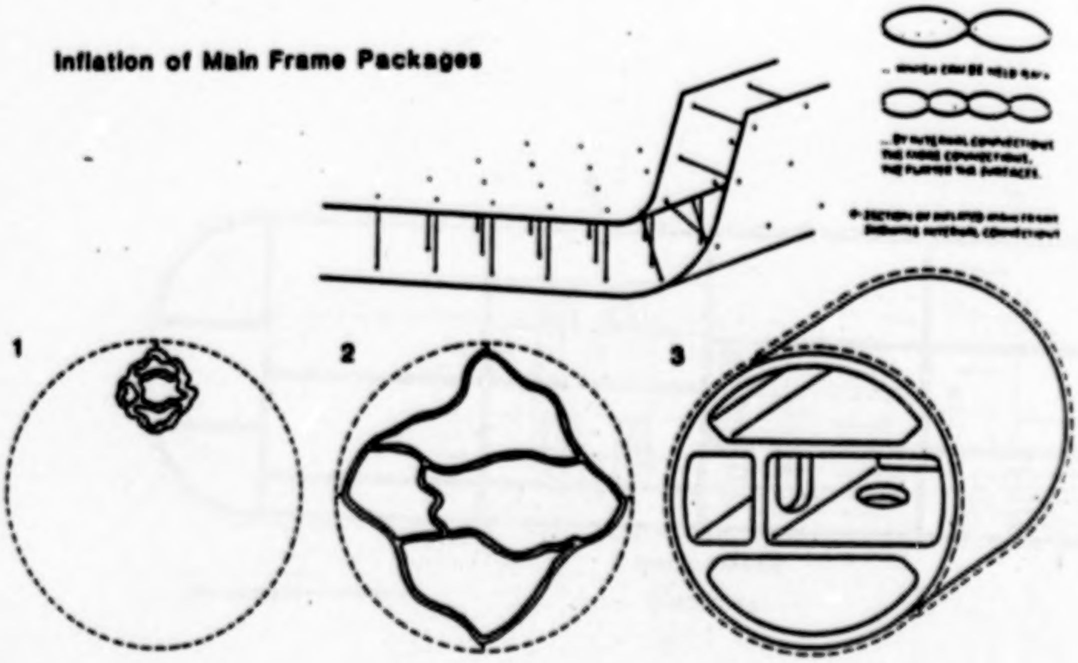
Inflatable Package Placement Method


Phase 1
Phase 2
Phase 3

Inflation of Main Frame Packages



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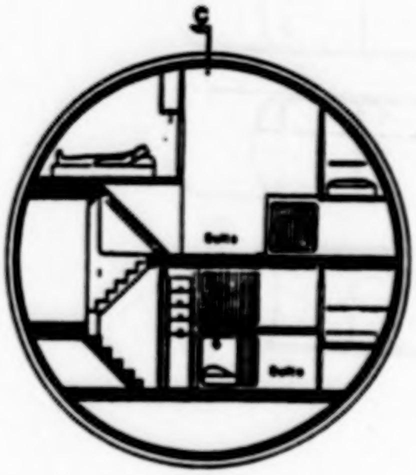
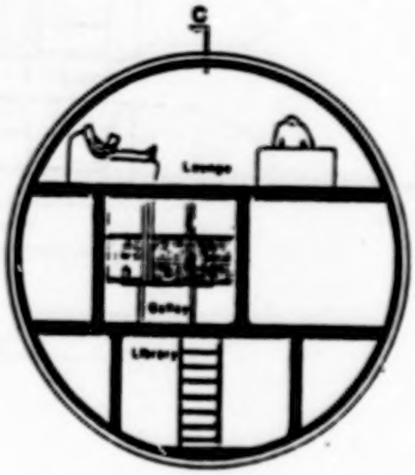
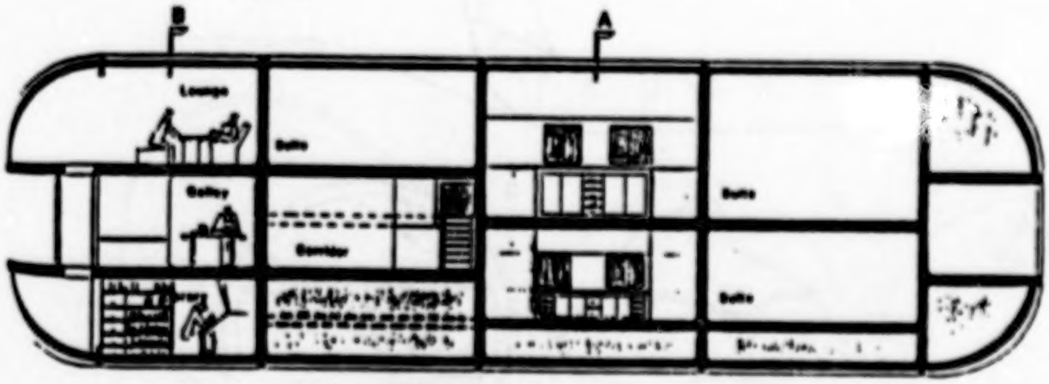

C
Suite
Suite

SECTION A


C
Lounge
Galley
Library

SECTION B

DORMITORY
TANK 6


B
A
Lounge
Suite
Galley
Corridor
Library
Suite
Suite
0'
10'
20'

DORMITORY TANK

SECTION C

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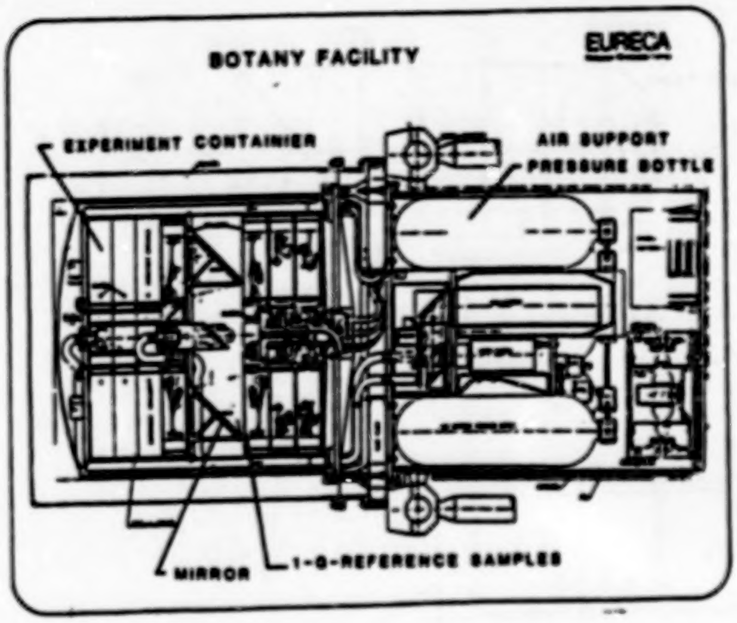
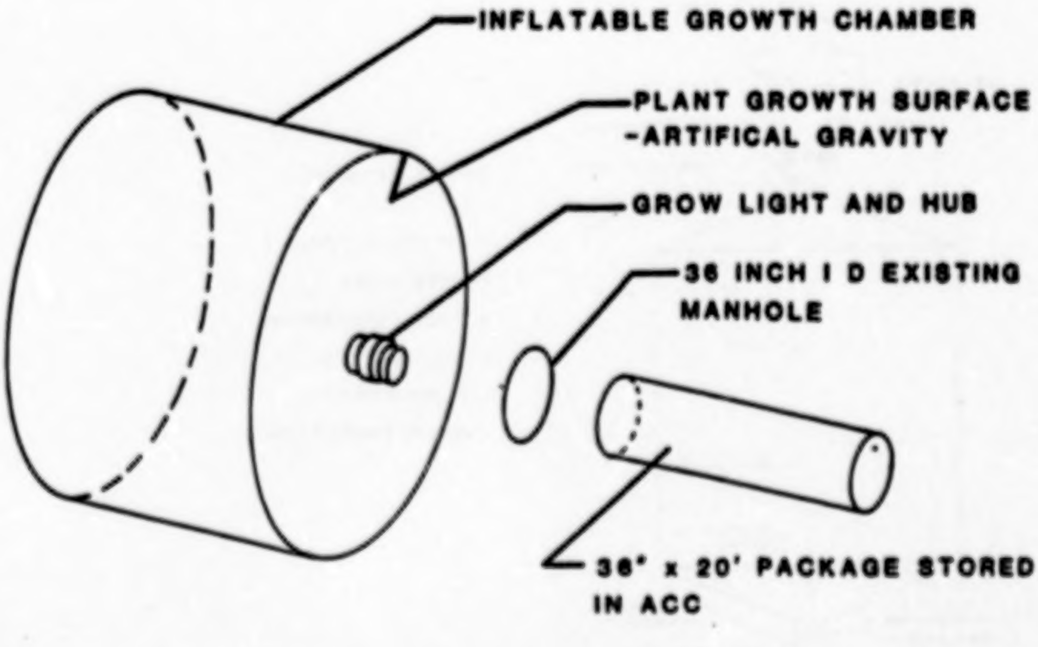
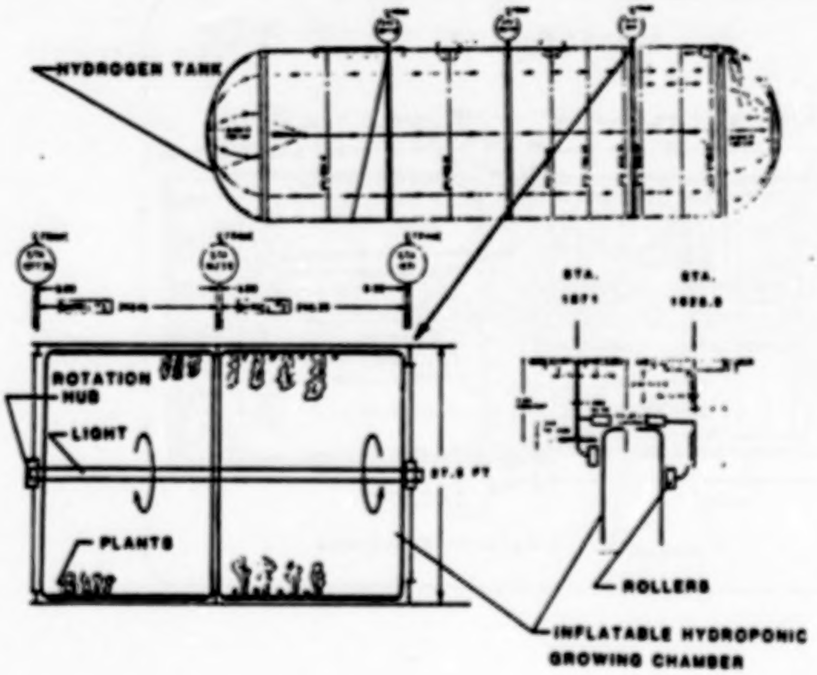

BOTANY FACILITY
EURECA
EXPERIMENT CONTAINER
AIR SUPPORT
PRESSURE BOTTLE
MIRROR
1-G-REFERENCE SAMPLES


INFLATABLE GROWTH CHAMBER
PLANT GROWTH SURFACE
-ARTIFICAL GRAVITY
GROW LIGHT AND HUB
36 INCH I D EXISTING
MANHOLE
36" x 20' PACKAGE STORED
IN ACC


HYDROGEN TANK
STA.
1871
STA.
1925.8
ROTATION HUB
LIGHT
27.5 FT
PLANTS
ROLLERS
INFLATABLE HYDROPONIC GROWING CHAMBER

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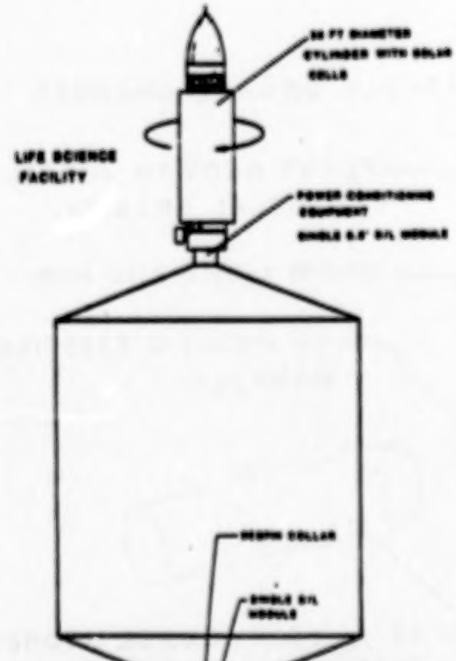
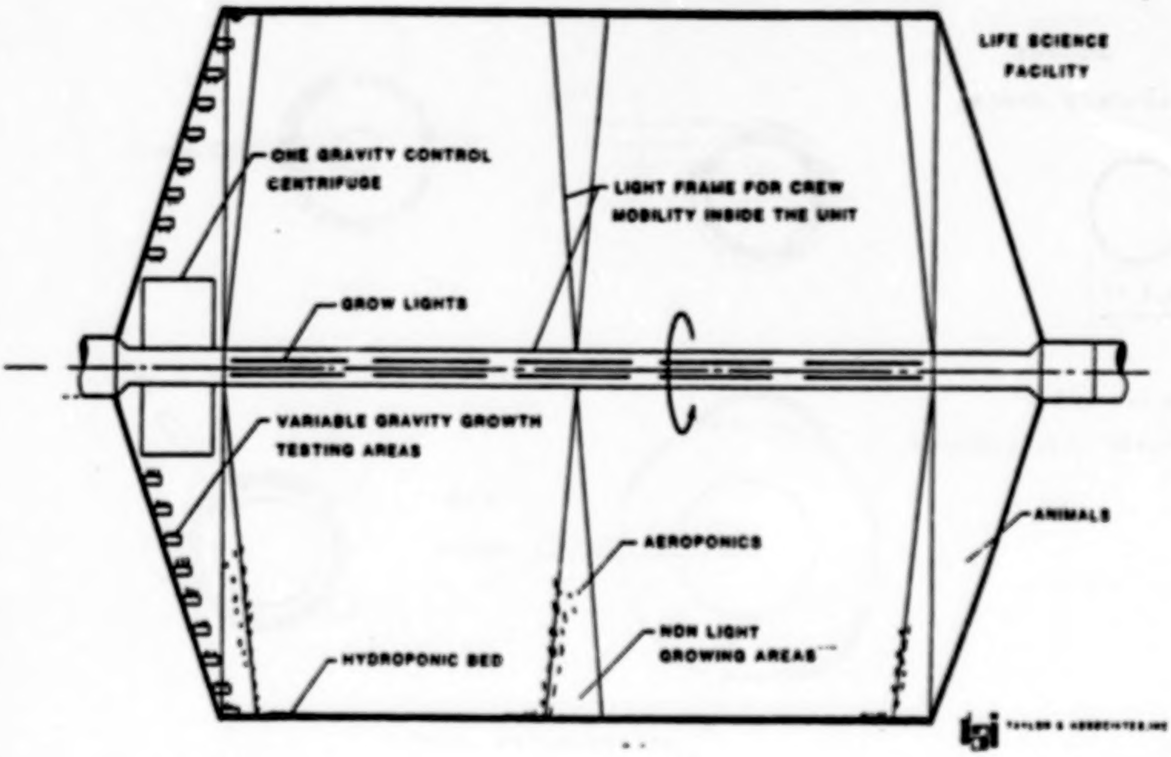
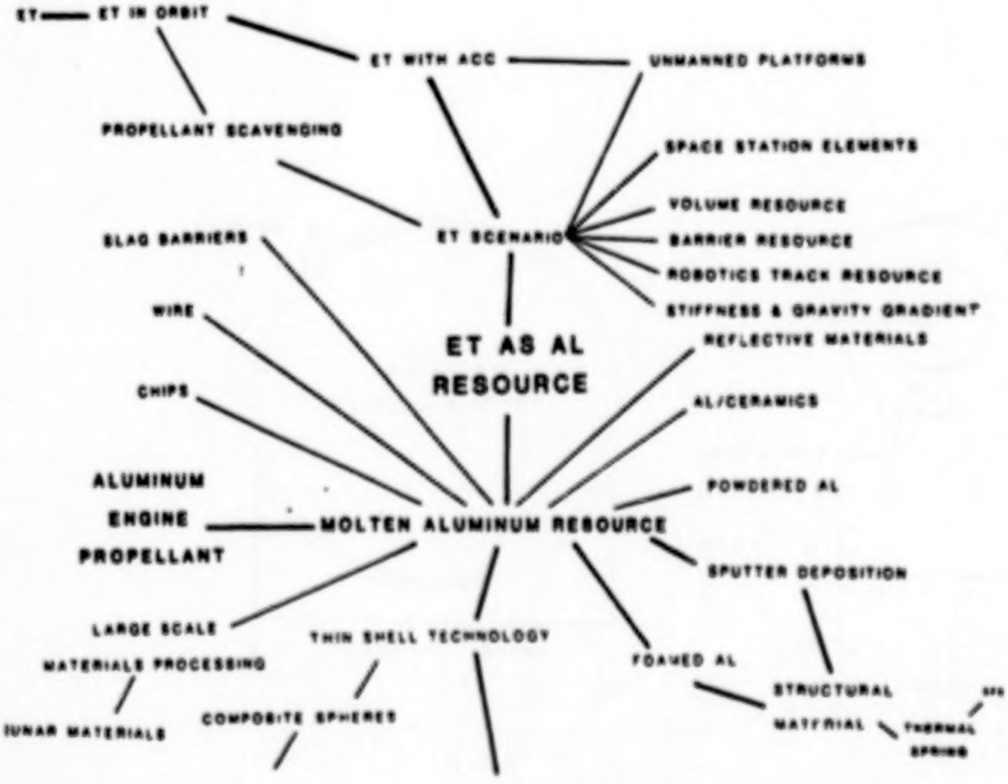

33 FT DIAMETER CYLINDER WITH SOLAR CELLS
LIFE SCIENCE FACILITY
POWER CONDITIONING EQUIPMENT
SINGLE 8.5' S/L MODULE
DESPIN COLLAR
SINGLE S/L MODULE
S/L LIFE SCIENCE LAB MODULE
STD 15' DIAMETER TANKS DETACHABLE
S/L CARGO MODULE DETACHABLE

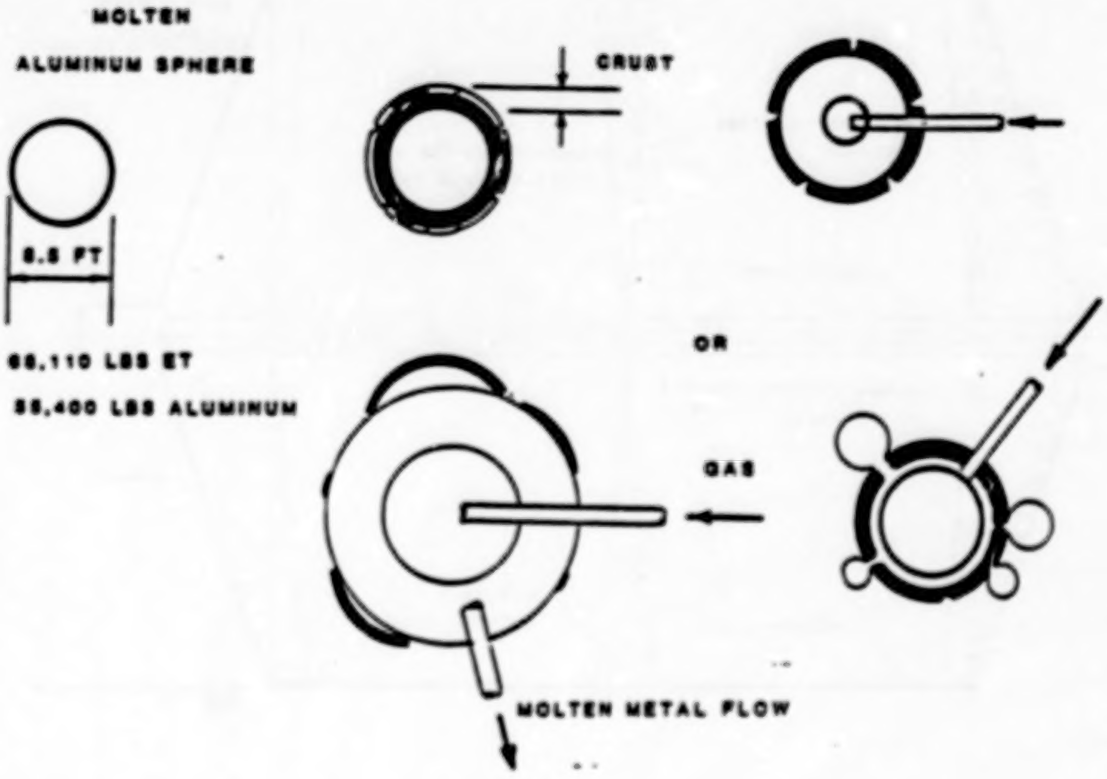
SPACE FARMING

- ARTIFICAL GRAVITY
- FREE FLYER
- FOOD PREPARATION
- $CO_2 \rightarrow O_2$
- PLANT GROWTH
- ANIMAL PRODUCTION


LIFE SCIENCE FACILITY
ONE GRAVITY CONTROL CENTRIFUGE
LIGHT FRAME FOR CREW MOBILITY INSIDE THE UNIT
GROW LIGHTS
VARIABLE GRAVITY GROWTH TESTING AREAS
ANIMALS
AEROPONICS
NON LIGHT GROWING AREAS
HYDROPONIC BED

TAYLOR & ASSOCIATES, INC


ET
ET IN ORBIT
ET WITH ACC
UNMANNED PLATFORMS
PROPELLANT SCAVENGING
SPACE STATION ELEMENTS
VOLUME RESOURCE
BARRIER RESOURCE
ROBOTICS TRACK RESOURCE
STIFFNESS & GRAVITY GRADIENT
ET SCENARIO
SLAG BARRIERS
WIRE
CHIPS
ET AS AL RESOURCE
REFLECTIVE MATERIALS
AL/CERAMICS
POWDERED AL
ALUMINUM ENGINE PROPELLANT
MOLTEN ALUMINUM RESOURCE
SPUTTER DEPOSITION
LARGE SCALE MATERIALS PROCESSING
THIN SHELL TECHNOLOGY
FOAMED AL
LUNAR MATERIALS
COMPOSITE SPHERES
STRUCTURAL MATERIAL
SPS
THERMAL SPRING


MOLTEN
ALUMINUM SPHERE
8.5 FT
66,110 LBS ET
55,400 LBS ALUMINUM
CRUST
OR
GAS
MOLTEN METAL FLOW

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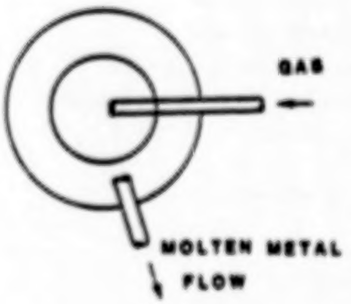
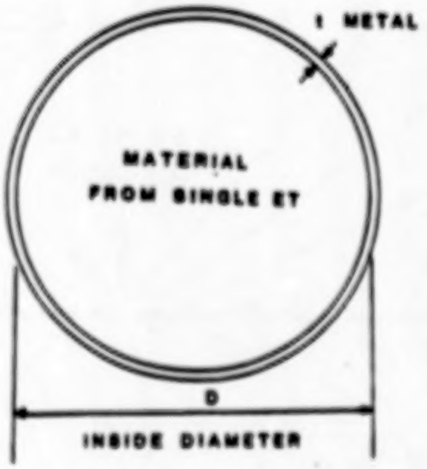
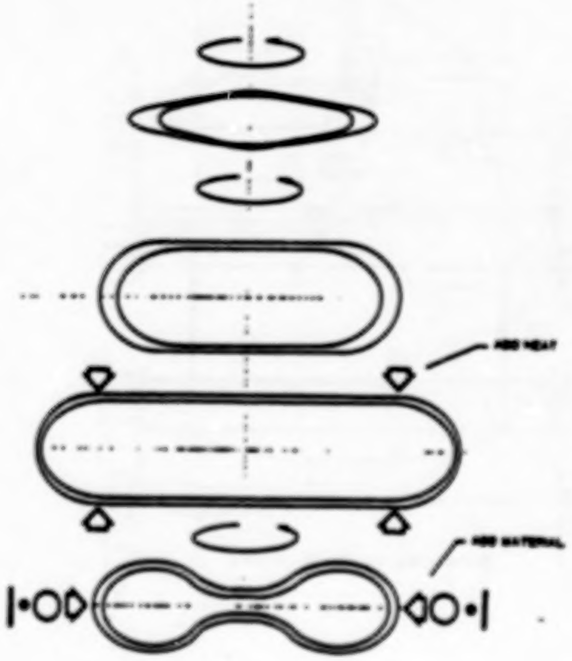
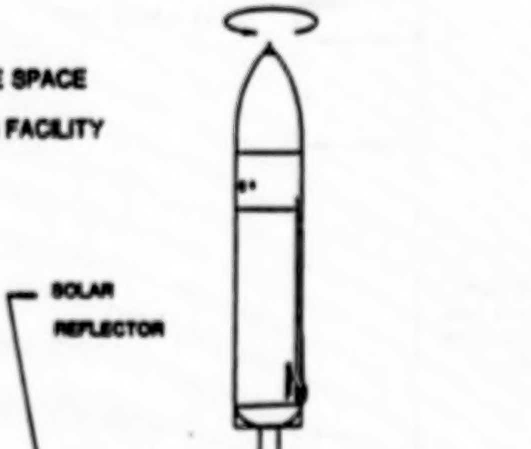

GAS
MOLTEN METAL
FLOW

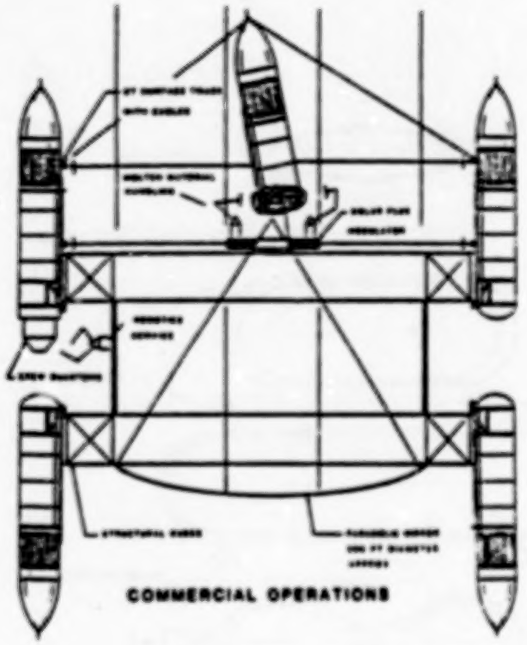
	t	D FEET
	1.046	10
	.211	30
1/8 INCH	.019	100


t METAL
MATERIAL
FROM SINGLE ET
D
INSIDE DIAMETER


ADD HEAT
ADD MATERIAL


SOLAR REFLECTOR
HANDLING ARM
ACC DEPLOYED
CONTROL MODULE

LARGE SCALE SPACE PROCESSING FACILITY


WITH CABLES
MOLTEN MATERIAL HANDLING
SOLAR FLUX REGULATOR
CREW QUARTERS
STRUCTURAL CUBES
PARABOLIC MIRROR
FT DIAMETER
APPROX

COMMERCIAL OPERATIONS

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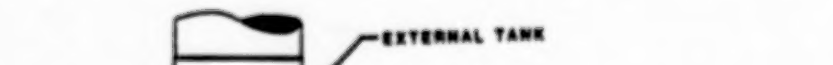
EXTERNAL TANK
BALANCE MASS FOR ROTATION AROUND LONG AXIS
AFT CARGO SKIRT
RMS WITH OC DEVISE
INFLATED ANTENNA
FUTURE INFLATABLE PAYLOADS TRANSPORTED IN SHUTTLE PAYLOAD BAY

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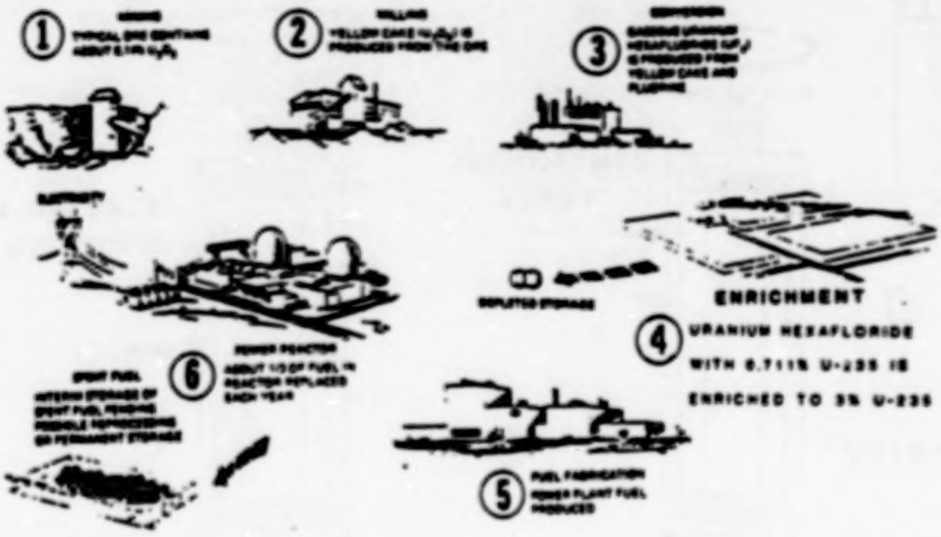
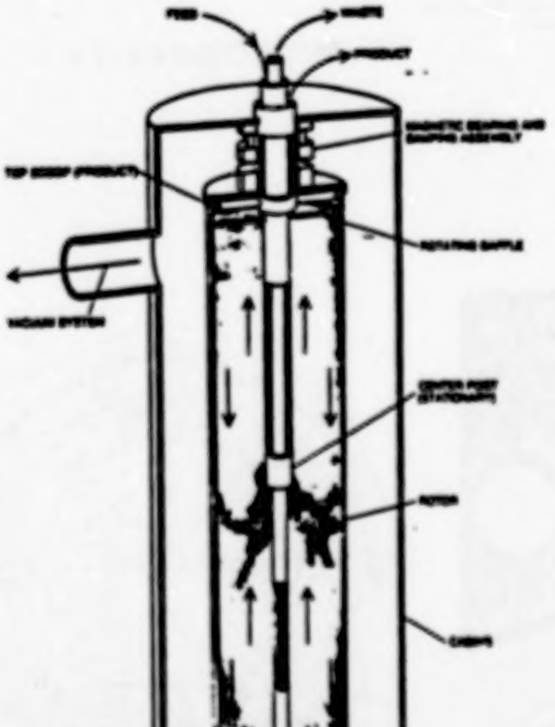

MINING
① TYPICAL ORE CONTAINS ABOUT 0.1% U3O8
MILLING
② YELLOW CAKE (U3O8) IS PRODUCED FROM THE ORE
CONVERSION
③ GASEOUS URANIUM HEXAFLUORIDE (UF6) IS PRODUCED FROM YELLOW CAKE AND FLUORINE
ELECTRICITY
DEPLETED STORAGE
ENRICHMENT
④ URANIUM HEXAFLORIDE WITH 0.711% U-235 IS ENRICHED TO 3% U-235
POWER REACTOR
⑥ ABOUT 1/3 OF FUEL IN REACTOR REPLACED EACH YEAR
SPENT FUEL
INTERIM STORAGE OF SPENT FUEL PENDING POSSIBLE REPROCESSING OR PERMANENT STORAGE
FUEL FABRICATION
⑤ POWER PLANT FUEL PRODUCED


FEED
WASTE
PRODUCT
MAGNETIC BEARING AND DAMPING ASSEMBLY
TOP SCOOP (PRODUCT)
ROTATING BAFFLE
VACUUM SYSTEM
CENTER POST (STATIONARY)
ROTOR
CASING
BOTTOM SCOOP (WASTE)
ELECTROMAGNETIC MOTOR
BOTTOM BEARING

INTERIOR OF A CENTRIFUGE is shown in this cutaway drawing. The thin-walled rotor is driven by a small electromagnetic motor attached to the bottom of the casing. The top end of the rotor is held in a vertical position by a magnetic bearing and does not touch stationary components. Gas is fed into and withdrawn from the rotor through the stationary center post, which holds three concentric tubes for the feed, the product and the waste. The stationary bottom scoop protrudes into the spinning gas and provides a mechanical means for driving the vertical flow of gas. The top scoop, which serves to remove the enriched product, is protected from direct interaction with the rotating gas by the baffle, which has holes allowing the enriched gas to be bled into the area near the scoop. The baffle is needed to keep the top scoop from imposing a vertical flow that would counteract the circular one generated by the bottom scoop.

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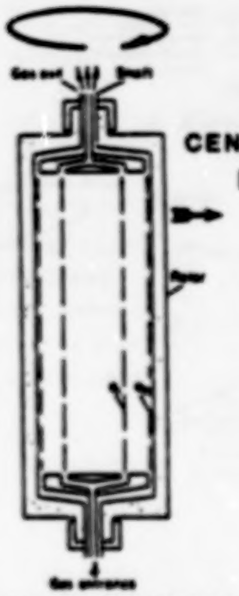
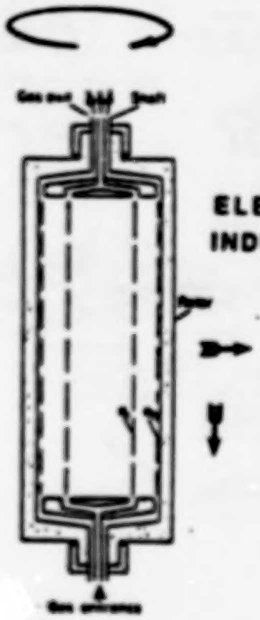
A countercurrent centrifuge.


Gas out
Shaft
Rotor
Gas entrance

CENTRIFUGAL FORCE

ONE GRAVITY

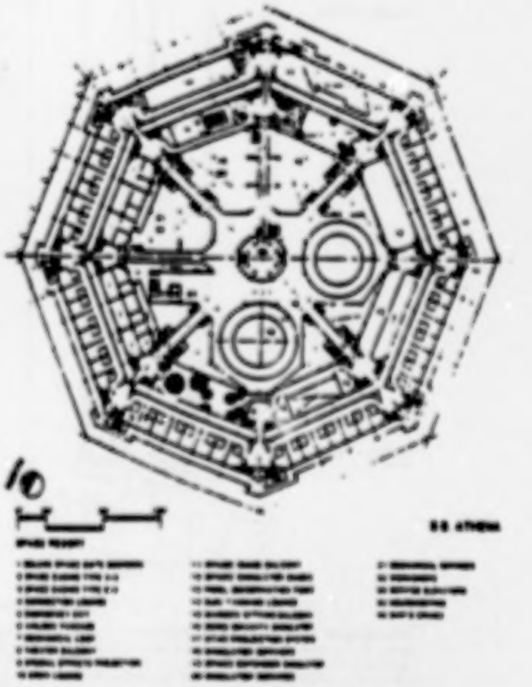
A countercurrent centrifuge.(17) (Reproduced by kind permission of the United States Atomic Energy Commission.)


Gas out
Shaft
Rotor
Gas entrance

ELECTRO MOTIVE INDUCTION FORCE

MICROGRAVITY

SPACE RESORT SPACE STATION - 250 MILE HIGH ORBIT


SPACE RESORT
SS ATHENA

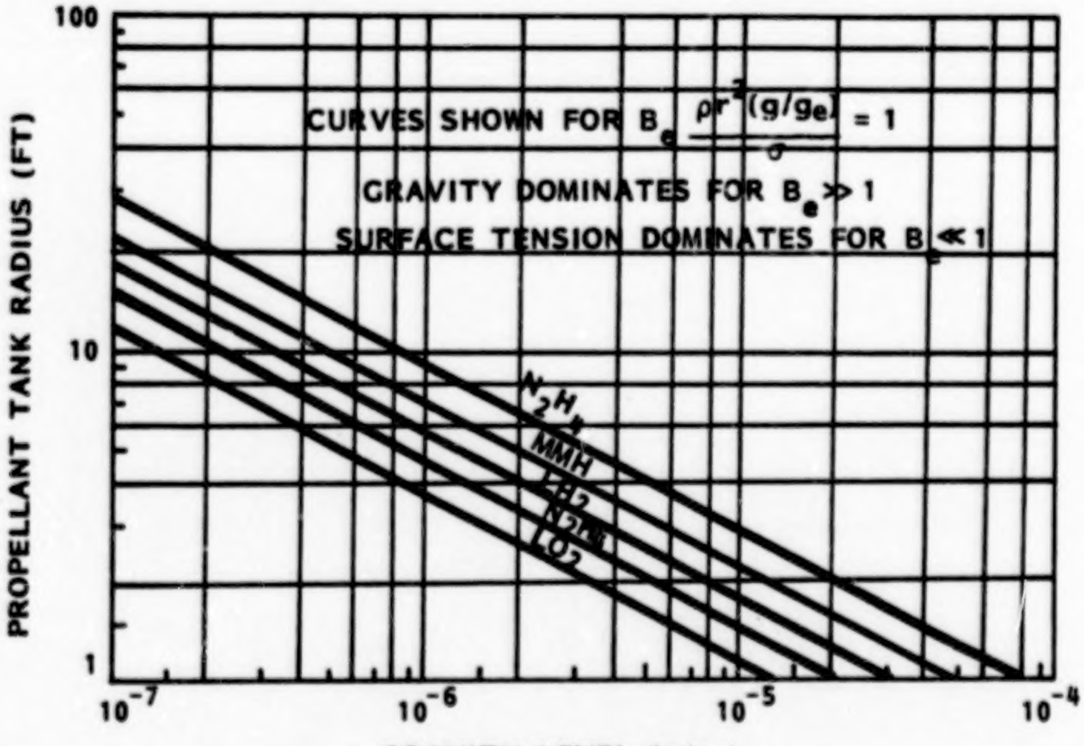
SRE	SPACE RESORTS ENTERPRISE	FLOOR PLAN DECK LEVEL 4

4 - TETHER TANK FARM

T. Tschirsi

WHY?

1. SAFETY
    1. STORAGE
    2. BERTHING/DOCKING
        - REMOTE
        - "CONST IN"
2. FACILITATE LIQUID TRANSFER
    1. FILL PROBLEMS
    2. DRAIN PROBLEMS



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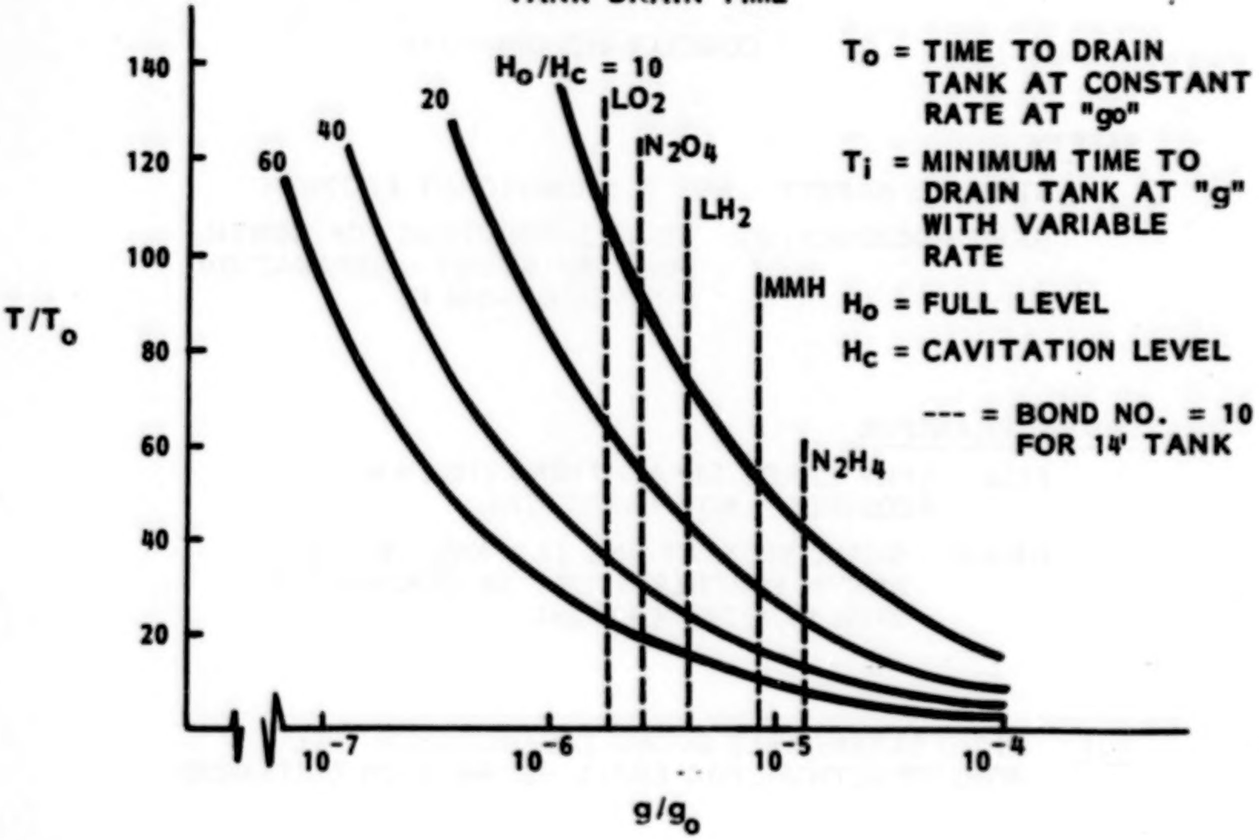
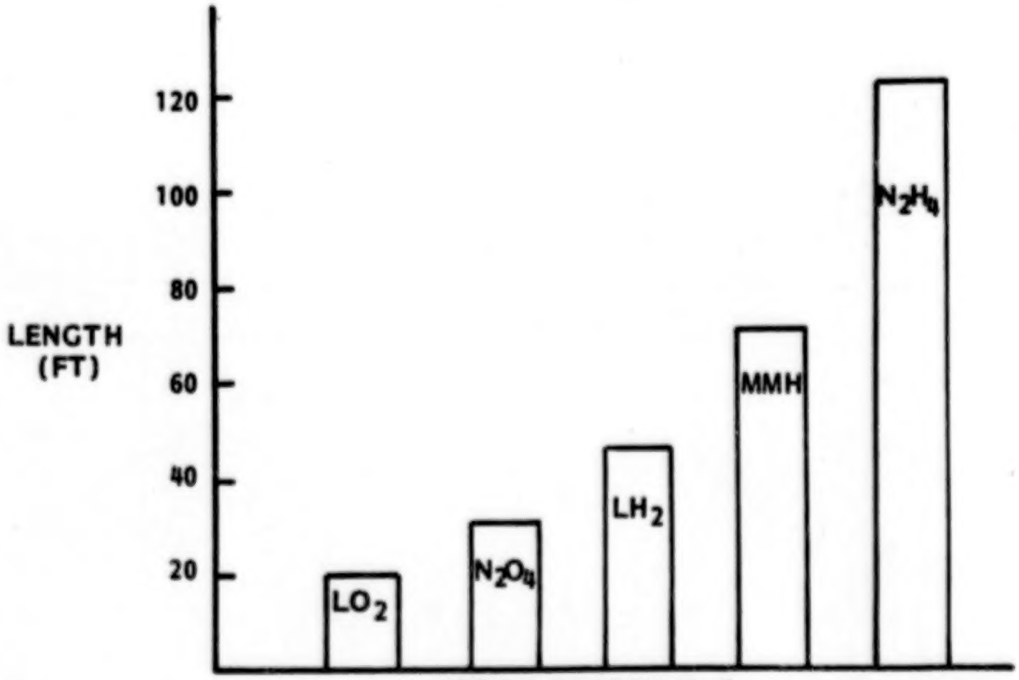
TANK DRAIN TIME



TETHER LENGTH*

BOND NO. = 10



*FROM SYSTEM C.G.

CONCLUDING OPINIONS

SAFETY

STORAGE SAFETY - NOT A SIGNIFICANT PROBLEM

BERTHING/DOCKING - REMOTE BERTHING FOR WORTH FURTHER STUDY - SEPARATION DISTANCE ~100 FT

LIQUID TRANSFER

FILL - VERY LARGE SEPARATIONS (100s KM) REQUIRED - NOT PRACTICAL

DRAIN - SMALL SEPARATIONS (0.1 KM) USEFUL WORTH FURTHER STUDY IN CONJUNCTION WITH REMOTE BERTHING

BUT: RIGID EXTENDABLE BOOMS (ASTROWASTE, ETC.) MORE PRACTICAL FOR SMALL SEPARATION DISTANCES

N85-20367

5 - ARTIFICIAL GRAVITY - TETHERS & CONTAINERS

D. Criswell

TETHERS AND CONTAINERS

DAVID R. CRISWELL, CALIFORNIA SPACE INSTITUTE, UNIVERSITY OF CALIFORNIA AT SAN DIEGO, A-021, LA JOLLA, CA 92093

Tethers used in conjunction with containers offer a means of enhanced control of basic variables such as local acceleration, pointing and orientation, and protected or controlled environments against particle or electromagnetic radiation. Local gravitational levels of a few 1 E-5 to 1 E-1 meters per second**2 may be provided in low Earth orbits with reasonable tether lengths and masses and with small rotational velocities (one turn per orbit). This acceleration can be provided without major expenditures of reaction mass. Some applications of tethers allow or even encourage the use of very large masses in orbit. This opens the possibilities for taking to orbit the External Tanks of the Space Transportation System (STS) and using them both as counter weight mass in tether systems and also to provide engineered volumes and structures in low Earth orbit or beyond. ETs can provide large volumes protected against the raw space environment. Within these volumes there can be some control over levels of mechanical disturbances (impacts, thermal cycling, plume impingment, ...). Protection can be provided against direct electromagnetic and particle radiation. Pressurization can be provided up to the order of one atmosphere in at least two separate large volumes per ET and possibly many small volumes in each inner tank region. Several applications of these levels of control come to mind.

Permanent occupancy of space will require the rapid exploration of the short and long term responses of many living organisms to the space environment or separated components of that environment. Tethers and ET facilities could provide the rapid establishment of laboratories in LEO within which to study living systems in a wide range of separate controlled environments for long periods of time. Extensive experiments could be conduced on the growth of many forms of life in small containers. The development of agricultural plants could be studied in microgravity to 0.1 g levels of gravity in large containers. ETs could be reworked to provide shielding of almost any desired thickness against particle radiation. This is important to provide several controlled environments for biological experiments. These and similar topics were explored (18 February 1983) in a workshop on biological uses of External Tanks in LEO which is available from the California Space Institute. Small and large versions of sealed ecology experiments could be supported by ET systems with tethers to provided orientation and low levels of gravity (Schwarzkopf S.H. and Stofan P.E., A chamber design for closed ecological systems research, ASME, 81-ENAs-37).

Tethers and ET derived containers might support large optical arrays which have been proposed for examining the very high energy components of cosmic rays. Dr. John Lindsay (Un. New Mexico) has proposed deploying a large set of fly's eyes telescopes in orbit which could monitor the atmosphere from above for the light emissions of air showers of particles induced by very high energy cosmic rays. Dr. David G. Kock (Smithsonian Institute, Cambridge, MA). has proposed a large area gamma-ray imaging telescope system which could be placed inside an ET and used to provide detailed mapping of small regions of the sky in the x-ray. Such a system would augment present and proposed x-ray observatories in LEO. It is likely that large containers may be advantageous in pursuing gravitational research. R. F. C. Vessot has provided a review of gravitational wave research experiments which could be performed in space (Aeronautics and Astronautics, 58-65, April 1983). Gravitational red shift, gyroscopic precession and interferometers might make use of large cryogenic volumes, long tethers, and long periods of undisturbed operations in large sealed volumes. Studies will be required to reveal the advantages and disadvantages for not simply single experiments but for systems of experiments in which the equivalent of dedicated national laboratories in space might be created. ETs and other dense mass provided onboard the STS as payload fillers might be reformed into spherical masses with multipole gravitational fields which cancel the higher moments of terrestrial, lunar and solar gravity to a high degree inside a small volume of an orbital craft. R. Forward (Hughes Research Laboratory) has suggested the pure research tool for use in space. ETVOS experiments and large fiber optics loops operated in interferometric mode might be used in large protected volume for research on the equivalence of inertial and gravitational mass. There have even been suggestions for gravimeters based on the gravitationally induced electric fields in batteries which could be used in space to measure gravity gradient fields of the Earth. Refer to M.M. Nieto, T. Goldman and V.P. Gutschick (GEOPHYSICS, vol 48, #1, p. 39-41, 1 January 1983). Research on critical phenomena in chemistry and physics might be advanced by experiments on chemical systems and mechanical analogues in space. The Nieto et al. paper suggests opportunities for pure research in chemistry and the extremely subtle effects of gravitational forces on atoms and molecules should be explored.

Growing interest exists in establishing materials industry operations in space and on the moon. Tethers and containers could provide the flexibility to develop equipment for use in gravitational levels from 0 to 0.1 g. ETs could provide containers for machinery, contain debris of productive processes and cleanliness or protection from outside influences. Environments of asteroids or the moon could be duplicated close to Earth.

Tethers and containers might be useful in providing orbiting laboratories within which to simulate conditions on various planets, moons, asteroids or debris rings in the solar system. For example, dielectric fluid spheres held together by electrostatic attraction to a central metal conductor could be used to perform fluid mechanics experiments in zero or low gravity which are impossible on Earth. A national laboratory for fluid mechanics research could be established which could be used to investigate planetary and stellar models, complex fluid flows and provide test cases for computational fluid dynamics facilities at such places as NASA-Ames or Los Alamos National Laboratory. Results will likely be applicable to many industrial problems on Earth such as flow in pipe lines, chemical processing and so on. It might also be possible to experimentally model the extremely slow and soft collisions of particles in the rings of Saturn which are thought to play an important role in determining the dynamics of the complex rings.

Tethers and containers will certainly provide the controlled environments within which the application of advanced manufacturing, assembly, control and robotics could be developed to aid off-Earth industry and science and the conduct of increasingly more complex space operations.

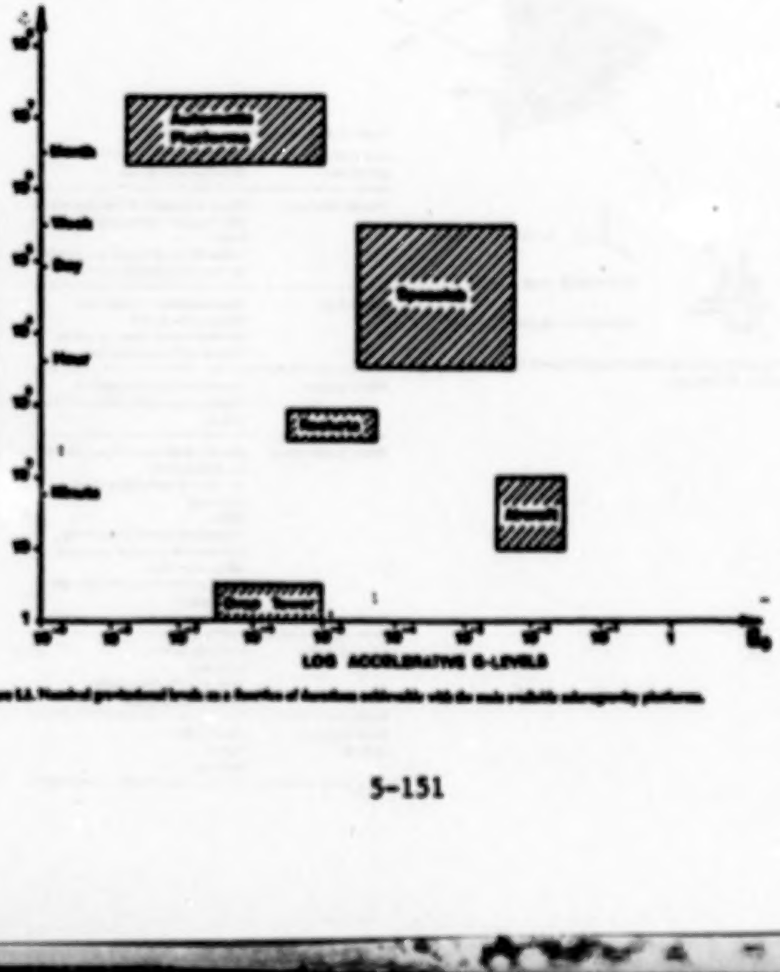
MICROGRAVITY ENVIRONMENTS

L. Napolitani

- LEVEL (INTENSITY)
- DIRECTION
- DURATION
- VOLUME
- QUALITY
  - PERSISTENCE OF NOMINAL VALUES THROUGHOUT DURATION
  - GRAVITY POLLUTION

MG PLATFORMS

- DROP TOWERS
- AIRCRAFTS
- SOUNDING ROCKETS
- SPACELAB
- SPACE STATIONS
- ➡ TETHERED PLATFORMS



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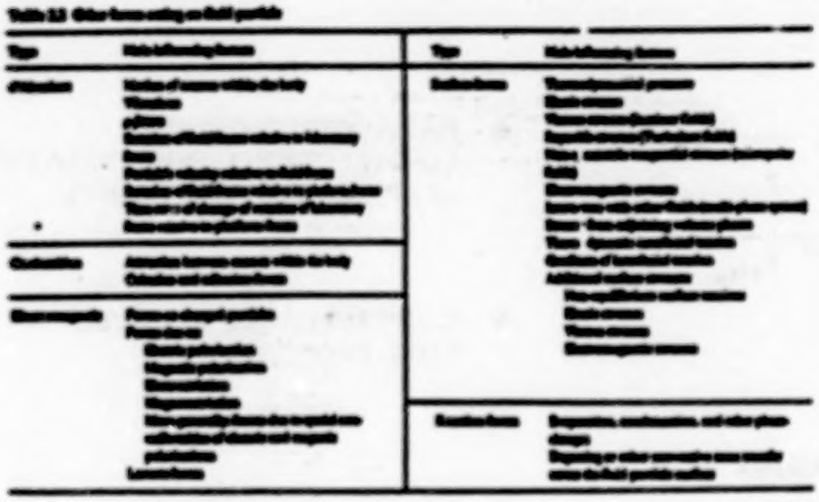
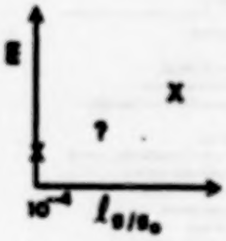


"CLASSICAL" PLATFORMS

- SINGLE POINT NOMINAL VALUES
- UNKNOWN DIRECTION
- TIME INDEPENDENT OR QUASI-STEADY NOMINAL VALUES
- DIFFERENT MG-QUALITY

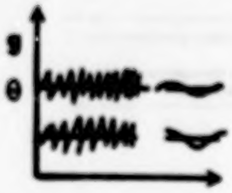
TETHERED PLATFORM

- CONTINUUM OF NOMINAL VALUES (INTENSITY, DIRECTION)
- TIME DIMENSION ADDED
- CONTROLLABILITY
- BETTER QUALITY

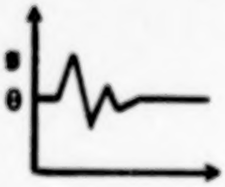


- **PARAMETRIC G-LEVEL (G-DIRECTION) INVESTIGATIONS (EXP. CURVE VS. POINT)**

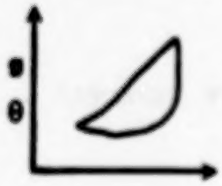
- **CONTROLLABLE G-LEVEL TIME PROFILES**



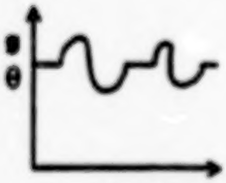
- **FREQUENCY-INTENSITY EFFECTS**



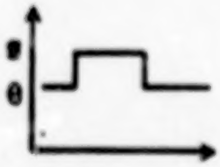
- **G-JITTERS**



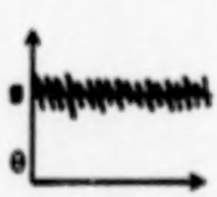
- **HYSTERESIS PHENOMENA**



- **TIME CYCLES**



- **INTERMITTENCY**



- **G-NOISE**

LIFE SCIENCES

- THRESHOLDS

MATERIAL SCIENCES

- CRYSTAL

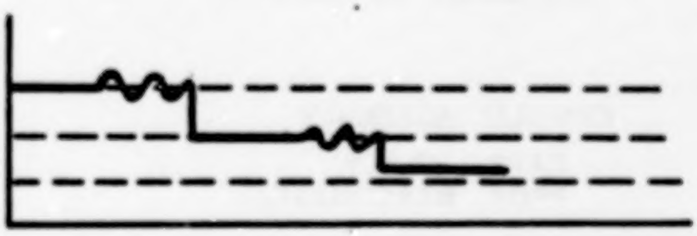
FLUID SCIENCES

- G-JITTERS

TECHNOLOGY

PROCESSES

- G-TUNING



MODES

- DEDICATED MISSION
- ADD-ON EXPERIMENTS
- GAS TYPE
- MULTIPLE TETHER

EUROPEAN LOW GRAVITY RESEARCH
ASSOCIATION

ELGRA

- **EUROPEAN SPACE AGENCY (ESA)**
- **STUDY GROUP**
  PARLIAMENTARY ASSOC.
  COUNCIL OF EUROPE

GENERAL ASSEMBLY
  CAPRI, ITALY
  PROF. BERGAMASCHI

6 - ARTIFICIAL GRAVITY TESTS USING THE ORBITER & SPACELAB-- THE E.T.

Joe Carroll

The basic concept is to start out on a swinging-tether ET-disposal operation, with a tether only a few kilometers long. When the "dumbbell" approaches the vertical, the RCS or OMS engines are fired, to speed up the swing and turn it into a spin. Several different rates of spin can easily be sampled, by using the thrusters to adjust the spin rate as desired. The experiment can be terminated by releasing the ET into a reentry trajectory when the system passes through the vertical. The choice of tether length, final spin rate, and release timing would determine the ET reentry footprint.

The reason for proposing a spacelab mission for this experiment is to use a mission with many zero-gee experiments, and start off with a period of controllable low-level gravity before switching to zero-gee experiments. A second reason is that spacelab missions should generally have the largest crews, and such a mission would be ideal for testing the response of humans to gravity levels in the .001-.1 gee range.

It appears that if the major trunnion fittings are used to anchor the tether on the orbiter side, and loads up to 1/3 the -Z ultimate load factors of 64,000 lbs are acceptable, then artificial gravity tests at up to 1/10 gee should be possible. A fitting that bridges the payload bay like the GaS bridge might be used, and/or (for greater stability) a tether that splits into several strands that attach at different points. Several suitable ET attachment points can probably be found, such as one of the aft attachment fittings. By keeping the tether under a few kilometers, the tether mass can be kept under a ton.

The major orbiter safety problems would appear to be the dynamic reaction of the system to the release of the tether, and the effects of tether recoil in the case of tether breakage. Careful studies would have to be made to decide what gee-levels are allowable for different attachment and release concepts. (Even if the maximum levels allowable are in the milligee to centigee range, many useful experiments may still be possible.)

The other major safety issue is ET reentry in the case of tether failure. This too would require careful study. It may be that the best solution is to use a tether only a few hundred meters long, so that significant gee levels can be obtained at low tip velocities. Then breakage need not cause reentry. ET reentry in this case would be by a retrorocket package. The idea of using an ET-disposal technique, but preventing it from being effective in that role, seems rather futile. However, such flight experiments could be invaluable in providing input to crucial decisions in space station design.

V. APPENDICES

Microgravity Tables

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LOWER REFERENCE ALTITUDE = 200 KM
INCREMENT IN ALTITUDE    = 100 KM
NUMBER OF INCREMENTS     = 6
ALTITUDE RANGE (R1) = 200 TO 800. STEP 100

MIN. LENGTH OF TETHER    = 0 KM
INCREMENT IN LENGTH      = .1 KM
NUMBER OF INCREMENTS     = 10
MAX. LENGTH OF TETHER    = 1 KM    (-VE LENGTH FOR TETHER
                                       ABOVE MAIN SATELLITE)

TETHER  /  ALTITUDE (KM)
LENGTH /
 (KM)          200.0        300.0        400.0        500.0        600.0        700.0        800.0

               MILLI-G  (= EARTH SURFACE GRAVITY UNIT/1000)

-   1.0     -  0.57     -  0.55     -  0.52     -  0.50     -  0.48     -  0.46     -  0.44
-   0.9     -  0.51     -  0.49     -  0.47     -  0.45     -  0.43     -  0.41     -  0.40
-   0.8     -  0.46     -  0.44     -  0.42     -  0.40     -  0.38     -  0.37     -  0.35
-   0.7     -  0.40     -  0.38     -  0.37     -  0.35     -  0.34     -  0.32     -  0.31
-   0.6     -  0.34     -  0.33     -  0.31     -  0.30     -  0.29     -  0.28     -  0.26
-   0.5     -  0.29     -  0.27     -  0.26     -  0.25     -  0.24     -  0.23     -  0.22
-   0.4     -  0.23     -  0.22     -  0.21     -  0.20     -  0.19     -  0.18     -  0.18
-   0.3     -  0.17     -  0.16     -  0.16     -  0.15     -  0.14     -  0.14     -  0.13
-   0.2     -  0.11     -  0.11     -  0.10     -  0.10     -  0.10     -  0.09     -  0.09
-   0.1     -  0.06     -  0.05     -  0.05     -  0.05     -  0.05     -  0.05     -  0.04
    0.0        0.00        0.00        0.00        0.00        0.00        0.00        0.00
    0.1        0.06        0.05        0.05        0.05        0.05        0.05        0.04
    0.2        0.11        0.11        0.10        0.10        0.10        0.09        0.09
    0.3        0.17        0.16        0.16        0.15        0.14        0.14        0.13
    0.4        0.23        0.22        0.21        0.20        0.19        0.18        0.18
    0.5        0.29        0.27        0.26        0.25        0.24        0.23        0.22
    0.6        0.34        0.33        0.31        0.30        0.29        0.28        0.26
    0.7        0.40        0.38        0.37        0.35        0.34        0.32        0.31
    0.8        0.46        0.44        0.42        0.40        0.38        0.37        0.35
    0.9        0.51        0.49        0.47        0.45        0.43        0.41        0.40
    1.0        0.57        0.55        0.52        0.50        0.48        0.46        0.44

***END***
>>
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LOWER REFERENCE ALTITUDE = 200 KM
INCREMENT IN ALTITUDE    = 100 KM
NUMBER OF INCREMENTS     = 6
ALTITUDE RANGE (R1) = 200 TO 800. STEP 100

MIN. LENGTH OF TETHER    = 0 KM
INCREMENT IN LENGTH      = 1 KM
NUMBER OF INCREMENTS     = 10
MAX. LENGTH OF TETHER    = 10 KM   (-VE LENGTH FOR TETHER
                                       ABOVE MAIN SATELLITE)

TETHER  /  ALTITUDE (KM)
LENGTH /
 (KM)          200.0        300.0        400.0        500.0        600.0        700.0        800.0

               MILLI-G  (= EARTH SURFACE GRAVITY UNIT/1000)

-  10.0     -  5.72     -  5.47     -  5.23     -  5.01     -  4.79     -  4.59     -  4.40
-   9.0     -  5.15     -  4.92     -  4.71     -  4.50     -  4.31     -  4.13     -  3.96
-   8.0     -  4.58     -  4.37     -  4.18     -  4.00     -  3.83     -  3.67     -  3.52
-   7.0     -  4.00     -  3.83     -  3.66     -  3.50     -  3.35     -  3.21     -  3.08
-   6.0     -  3.43     -  3.28     -  3.14     -  3.00     -  2.87     -  2.75     -  2.64
-   5.0     -  2.86     -  2.73     -  2.61     -  2.50     -  2.40     -  2.30     -  2.20
-   4.0     -  2.29     -  2.19     -  2.09     -  2.00     -  1.92     -  1.84     -  1.76
-   3.0     -  1.72     -  1.64     -  1.57     -  1.50     -  1.44     -  1.38     -  1.32
-   2.0     -  1.14     -  1.09     -  1.05     -  1.00     -  0.96     -  0.92     -  0.88
-   1.0     -  0.57     -  0.55     -  0.52     -  0.50     -  0.48     -  0.46     -  0.44
    0.0        0.00        0.00        0.00        0.00        0.00        0.00        0.00
    1.0        0.57        0.55        0.52        0.50        0.48        0.46        0.44
    2.0        1.14        1.09        1.04        1.00        0.96        0.92        0.88
    3.0        1.71        1.64        1.57        1.50        1.44        1.38        1.32
    4.0        2.29        2.18        2.09        2.00        1.91        1.83        1.76
    5.0        2.86        2.73        2.61        2.50        2.39        2.29        2.20
    6.0        3.43        3.28        3.13        3.00        2.87        2.75        2.64
    7.0        4.00        3.82        3.65        3.50        3.35        3.21        3.08
    8.0        4.57        4.37        4.18        4.00        3.83        3.67        3.52
    9.0        5.14        4.91        4.70        4.50        4.30        4.12        3.96
   10.0        5.71        5.46        5.22        4.99        4.78        4.58        4.39

***END***
>>
```

```
LOWER REFERENCE ALTITUDE = 200 KM
INCREMENT IN ALTITUDE    = 100 KM
NUMBER OF INCREMENTS     = 6
ALTITUDE RANGE (R1) = 200 TO 800, STEP 100

MIN. LENGTH OF TETHER    = 0 KM
INCREMENT IN LENGTH      = 10 KM
NUMBER OF INCREMENTS     = 10
MAX. LENGTH OF TETHER    = 100 KM     (-VE LENGTH FOR TETHER
                                       ABOVE MAIN SATELLITE)


TETHER  /  ALTITUDE (KM)
LENGTH /
 (KM)          200.0         300.0         400.0         500.0         600.0         700.0         800.0

               MILLI-G  (= EARTH SURFACE GRAVITY UNIT/1000)

- 100.0      - 57.82       - 55.25       - 52.83       - 50.55       - 48.40       - 46.37       - 44.45
-  90.0      - 51.98       - 49.67       - 47.49       - 45.45       - 43.51       - 41.69       - 39.97
-  80.0      - 46.15       - 44.10       - 42.17       - 40.35       - 38.64       - 37.02       - 35.49
-  70.0      - 40.33       - 38.54       - 36.86       - 35.27       - 33.77       - 32.36       - 31.02
-  60.0      - 34.53       - 33.00       - 31.56       - 30.20       - 28.91       - 27.70       - 26.56
-  50.0      - 28.74       - 27.47       - 26.27       - 25.14       - 24.07       - 23.06       - 22.11
-  40.0      - 22.97       - 21.95       - 20.99       - 20.09       - 19.23       - 18.43       - 17.67
-  30.0      - 17.21       - 16.44       - 15.72       - 15.05       - 14.41       - 13.81       - 13.24
-  20.0      - 11.46       - 10.95       - 10.47       - 10.02       -  9.60       -  9.19       -  8.82
-  10.0      -  5.72       -  5.47       -  5.23       -  5.01       -  4.79       -  4.59       -  4.40
    0.0         0.00          0.00          0.00          0.00          0.00          0.00          0.00
   10.0         5.71          5.46          5.22          4.99          4.78          4.58          4.39
   20.0        11.40         10.90         10.43          9.98          9.56          9.16          8.78
   30.0        17.09         16.33         15.62         14.95         14.32         13.72         13.15
   40.0        22.76         21.75         20.81         19.91         19.07         18.27         17.52
   50.0        28.42         27.16         25.98         24.86         23.81         22.82         21.88
   60.0        34.06         32.56         31.14         29.80         28.54         27.35         26.23
   70.0        39.69         37.94         36.29         34.73         33.27         31.88         30.57
   80.0        45.31         43.31         41.43         39.65         37.98         36.39         34.90
   90.0        50.92         48.67         46.56         44.56         42.68         40.90         39.22
  100.0        56.51         54.02         51.67         49.46         47.37         45.40         43.53

***END***
```

N85-20368

REPORT OF THE
CONSTELLATIONS PANEL

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CONSTELLATIONS PANEL

David J. Bents	NASA, Lewis Research Center
George von Tiesenhausen	NASA-MSFC
Charles A. Lundquist	University of Alabama in Huntsville
Pete Swan	University of California, LA/ JPL
Harris L. Mayer	Aerospace Corp.
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Silvio Bergamasui	PADUA University
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Frank Williams, Co-Chairman	Martin Marietta, New Orleans (ET Prog.)
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Thomas Taylor	TT Assoc.
Joseph Carroll	California Space Inst.
David Criswell	California Space Inst.

I. INTRODUCTION

The NASA tether working group provided Fig. 1 as a starting point for the definition of "Constellations."

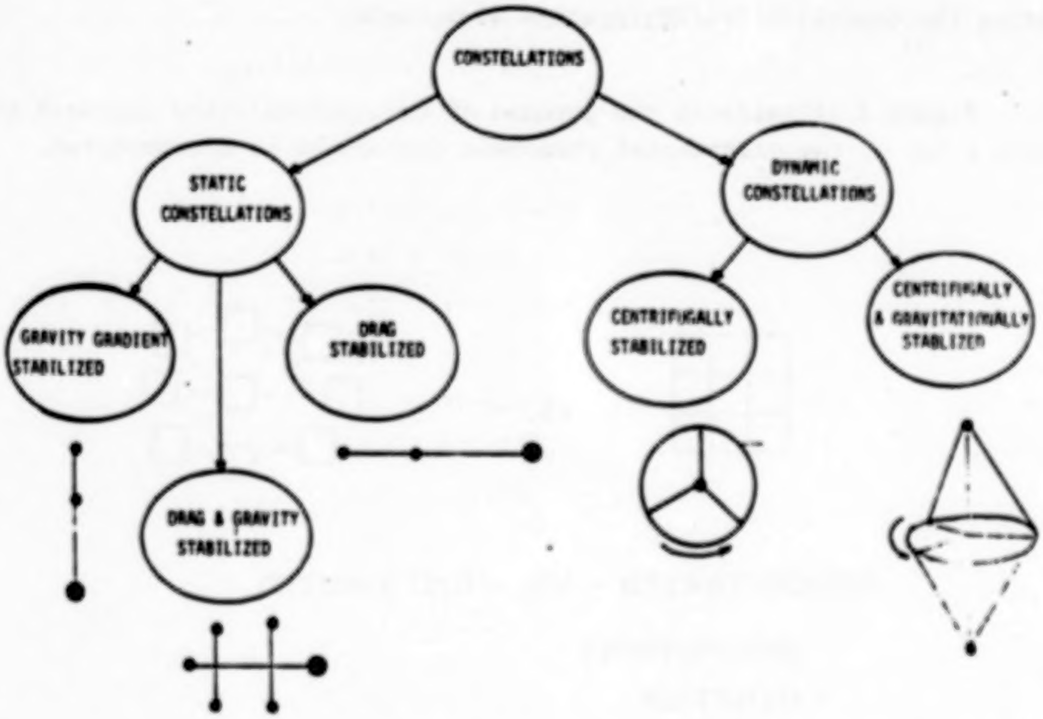

CONSTELLATIONS
STATIC CONSTELLATIONS
DYNAMIC CONSTELLATIONS
GRAVITY GRADIENT STABILIZED
DRAG STABILIZED
DRAG & GRAVITY STABILIZED
CENTRIFUGALLY STABILIZED
CENTRIFUGALLY & GRAVITATIONALLY STABLIZED

Figure 1. Tethered Constellations

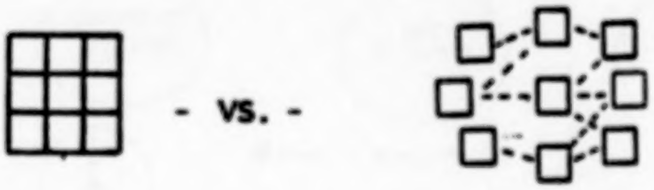
The panel used this as a point of departure and made the following modifications:

1. Suggest that the combined centrifugally and gravitationally stable configuration not be given strong consideration. This not to imply that the configuration is not feasible but rather to highlight the fact that the coupling of the two stabilizing forces will provide "limitations" to its applications. If compelling reasons dictate such applications it should be given consideration.

2. Constellations that include both tethers and fixed or rigid members should be added.

The purpose of a constellation is to provide a mode of "distributing" space systems in a method that could be advantageous and not eliminating the consolidation/aggregation advantages.

Figure 2 illustrates the purpose of the constellation approach and lists a few of the distributed phenomena that could be accommodated.



CONCENTRATED - VS. - DISTRIBUTED

- ENVIRONMENT
- UTILITIES
- LOGISTICS
- SAFETY
- GROWTH/FLEXIBILITY

Figure 2. Purpose of Constellation

II. APPLICATION REGIONS FOR CONSTELLATION

Starting from the definitions of the introduction, a first assessment was made to define the applicability of stabilization concepts to various orbital conditions. Table 1 defines this applicability against orbital altitudes, considering two cases:

Low earth orbits
Geostationary orbits

TABLE 1

CONSTELLATIONS STABILIZATION FEASIBILITY

STAB ORBIT	GRAV GRAD	ATM DRAG	GRAV GRAD + ATM DRAG	GRAV GRAD + MAG.	GRAV GRAD + J22	GRAV GRAD + MOMEN. TETHER	DYNAMIC (SPIN)	DYNAMIC + GRAV GRAD
LOW ORBIT	YES	YES	YES	YES	NO	YES	YES	NO
GEO ORBIT	YES	NO	NO	TBD	YES	YES	YES	NO
CONSTELL. DIMENSIONS	1	1	1-2	2	2	2-3	2-3	3

Table 1 was obtained from the following considerations.

LEO and GEO Scenarios for Constellations

LEO

- **Comparatively larger tension induced by gravity gradient**
- **Possibility of Shuttle assisted operations**
- **Manned constellations**
- **Tether lengths up to 300 km (to be assessed better)**
- **Possibility to exploit air drag and Earth's magnetic field as stabilizing forces**

Perturbations in LEO

- **Atmospheric drag, dependent on altitude and, to a lesser extent, on inclination (to be investigated for air drop control)**
- **Solar radiation pressure (earth shadow - sunshine)**
- **Earth obleteness**
- **Magnetic Earth field**

GEO

- **Gravity gradient tension reduced by two orders of magnitude (with the same tether length and same masses)**
- **Automatic constellations**
- **Tether lengths up to 5000 km (to be assessed better)**

Perturbations

- **Triaxiality of the Earth (J_{22} Form)**
- **Solar radiation pressure**
- **Luni-solar torques**

AIR DRAG

It can be exploited to separate platforms in the direction normal to the local vertical in the orbit plane.

Dependent on:

- Orbit altitude
- Area/mass ratio of different components (increasing from leading to trailing)
- Short tether length allowed

- A trade-off must be looked for between tether tension and orbital decay
- One dimensional constellation

GRAVITY GRADIENT AND AIR DRAG

Drag forces should be large enough to permit tether tension control in the flight direction and small enough to be comparable to other perturbations. Optimization is possible by adjusting:

- orbit altitude
- tethers lengths
- area on mass ratio of constellation components

- It might result from the study that the altitude "windows" at which drag control is viable is too narrow.
- Two dimensional constellation

MAGNETIC CONTROL

This control exploits the forces arising by the interaction of Earth's magnetic field and electric loops in the tethers.

Dependent on:

- Orbit. This control is possible only in LEO due to the rapid decrease of the Earth's magnetic field as altitude increases.
- Dedicated on-board power supply

- Two dimensional constellation

GRAVITY GRADIENT AND J_{22}

The ellipticity of the Earth equator originates two stable and two unstable (saddle) points at GEO synchronous altitude. These points are fixed with respect to Earth. If a mass is placed near an unstable point with zero relative velocity, it drifts toward the nearest stable point; therefore, if a dumbbell is located with its end masses on off sides of a saddle point, the repulsive force keeps the tether in tension.

1 dimensional constellation with J_{22} effect along
2 dimensional constellation with gravity gradient added

GRAVITY GRADIENT AND MOMENTUM TETHERS

In order to stabilize a two or three dimensional constellation, forces generated by the so-called momentum tethers can be exploited. These devices can provide tension forces in the horizontal direction both in the orbital plane and out of plane.

The massive tethers, actually are rapidly moving belts; tension forces are provided by momentum wheels round each terminus.

Applicable both in LEO and GEO, 2 and 3 dimensional constellations.

III. TETHER CONSTELLATION APPLICATION CONCEPTS

Numerous constellation applications were discussed and assessed. Due to the short time and restricted backgrounds of the participants the panel believes that a more extensive effort needs to be undertaken to consider other applications of constellations.

The following material is provided to illustrate some of the application concepts. A detailed assessment was not made on the concepts presented and their feasibility cannot be assumed. Figure 3 illustrates a nuclear power tethered platform.

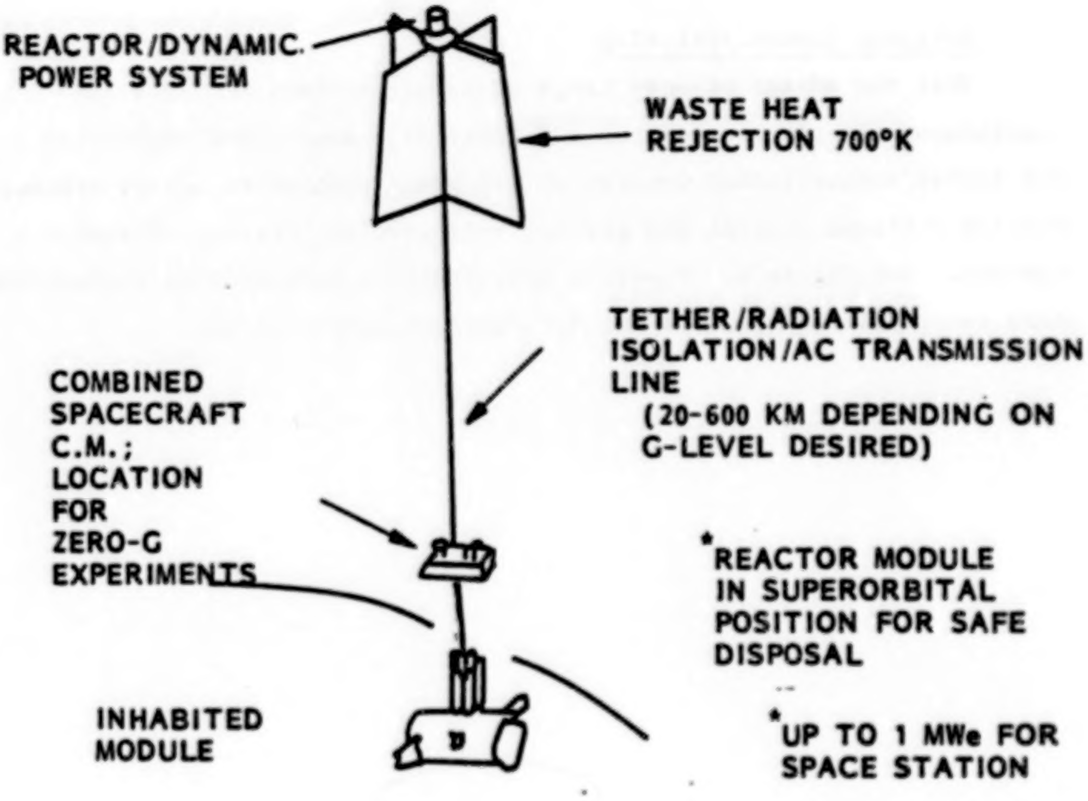

REACTOR/DYNAMIC POWER SYSTEM
WASTE HEAT REJECTION 700°K
TETHER/RADIATION ISOLATION/AC TRANSMISSION LINE (20-600 KM DEPENDING ON G-LEVEL DESIRED)
COMBINED SPACECRAFT C.M.; LOCATION FOR ZERO-G EXPERIMENTS
*REACTOR MODULE IN SUPERORBITAL POSITION FOR SAFE DISPOSAL
INHABITED MODULE
*UP TO 1 MWe FOR SPACE STATION

Figure 3. Nuclear Powered Tethered Platform

One concept, that of a very large tether comprised of a group of external tanks illustrated in the overview paper by I. Becky, was assessed from a stability standpoint and is included as Section IV of this panel report.

It was the consensus of the panel that it would be very desirable to develop "Mass in Orbit" for the subsequent use on various tether and constellation concepts. The ET is considered to be an excellent mass to acquire on orbit in that it can be delivered to orbit at basically no expense.

The use of the ET on orbit is not limited to its application to the constellation concepts - i.e. use as a mass for momentum exchange in the transportation panel.

Attitude Control/Pointing

With the advent of very large structure/systems in space the requirement for precise control and point will demand new techniques. The tether/constellation concept offers great promise to adjust orbits, provide attitude control and provide very precise pointing of such systems. See Figure 4. Figure 5 illustrates a more complex concept that uses constellation concepts for attitude/position control.

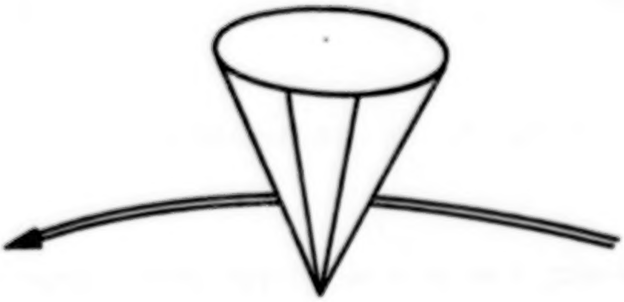


Figure 4. Attitude Control/Pointing

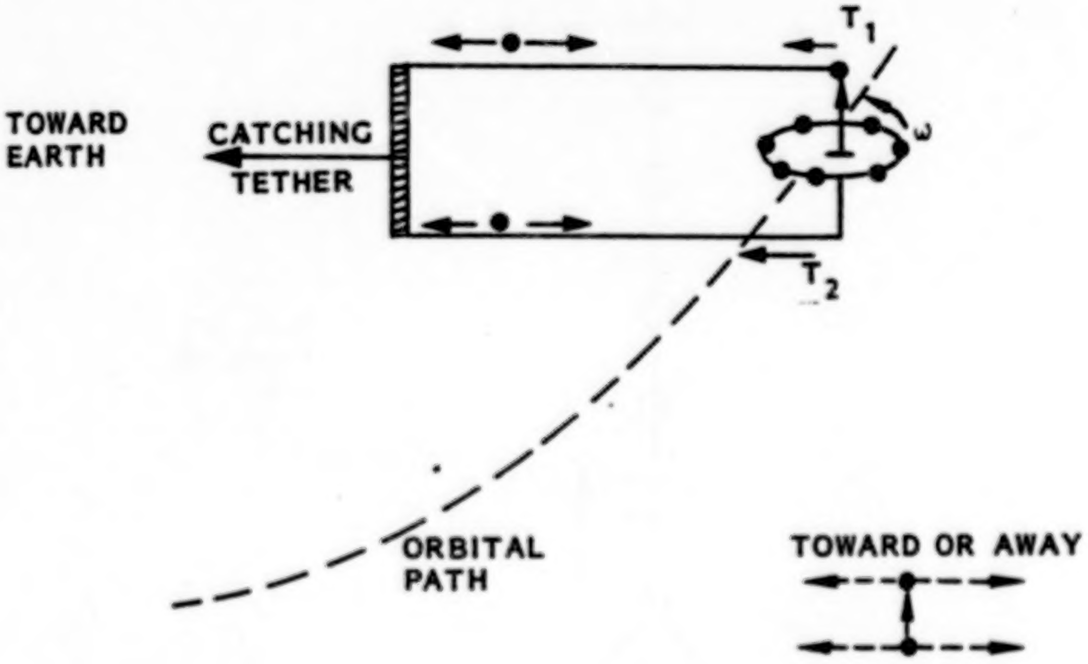

TOWARD EARTH
CATCHING TETHER
T_1
ω
T_2
ORBITAL PATH
TOWARD OR AWAY

Figure 5. Tether Tension Force to Control Spin Axis

Figure 6 illustrates concepts that would add to the survivability of space assets. The concept could have application in 1 dimensional modes of gravity gradient on drag stabilized approaches or in a 2 dimensional cluster approach (not illustrated). The assets could be moved within the constellation vs time.

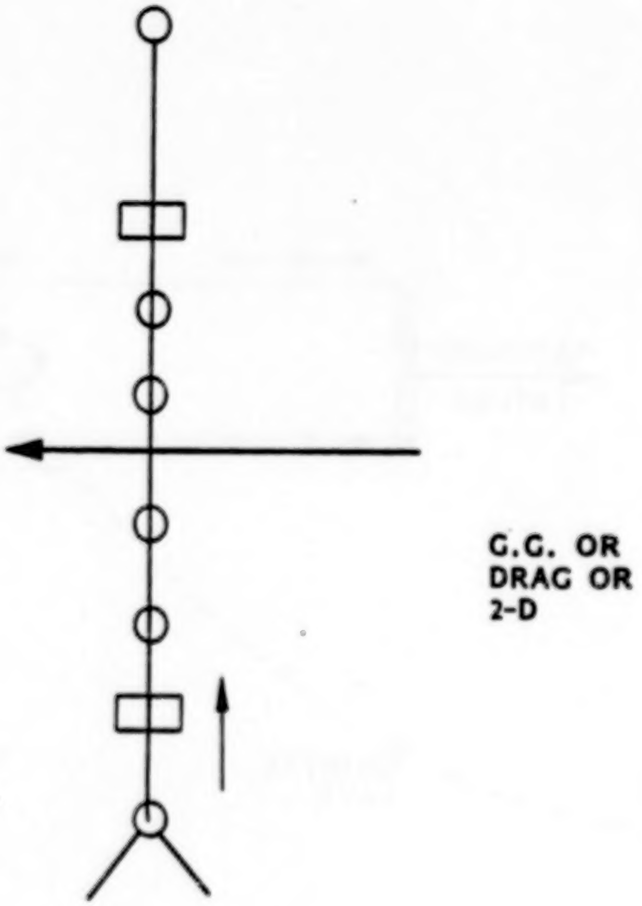


Figure 6. Survivability of Space Assets

An overall architecture of a major space station/activity using constellations is presented in Figure 7 and Tables 2 and 3. This involves a series of constellations in a single orbit that offers service to one another and compliments the totality of the system.

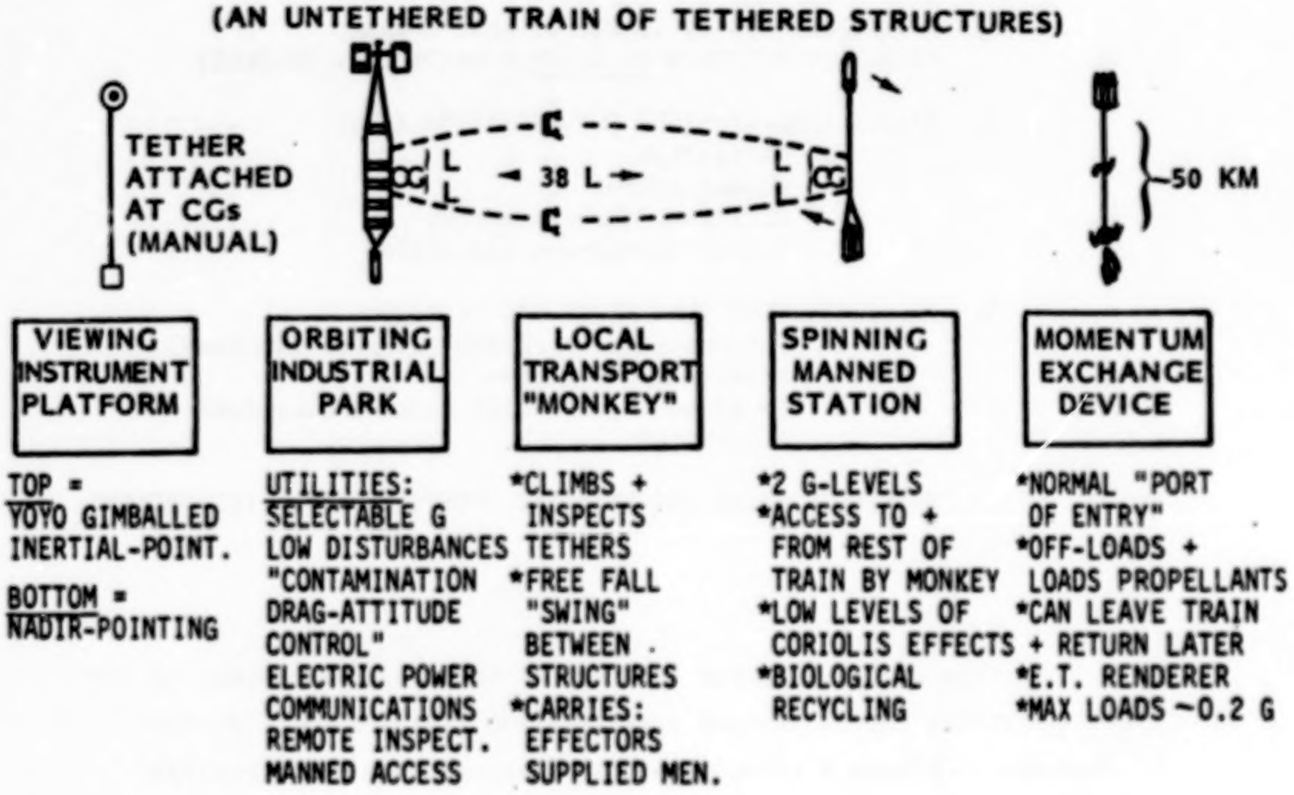

(AN UNTETHERED TRAIN OF TETHERED STRUCTURES)
TETHER
ATTACHED
AT CGs
(MANUAL)
L
L
38 L
L
L
CG
CG
50 KM
VIEWING INSTRUMENT PLATFORM
ORBITING INDUSTRIAL PARK
LOCAL TRANSPORT "MONKEY"
SPINNING MANNED STATION
MOMENTUM EXCHANGE DEVICE
TOP =
YOYO GIMBALLED
INERTIAL-POINT.
BOTTOM =
NADIR-POINTING
UTILITIES:
SELECTABLE G
LOW DISTURBANCES
"CONTAMINATION
DRAG-ATTITUDE
CONTROL"
ELECTRIC POWER
COMMUNICATIONS
REMOTE INSPECT.
MANNED ACCESS
*CLIMBS +
INSPECTS
TETHERS
*FREE FALL
"SWING"
BETWEEN
STRUCTURES
*CARRIES:
EFFECTORS
SUPPLIED MEN.
*2 G-LEVELS
*ACCESS TO +
FROM REST OF
TRAIN BY MONKEY
*LOW LEVELS OF
CORIOLIS EFFECTS
*BIOLOGICAL
RECYCLING
*NORMAL "PORT
OF ENTRY"
*OFF-LOADS +
LOADS PROPELLANTS
*CAN LEAVE TRAIN
+ RETURN LATER
*E.T. RENDERER
*MAX LOADS ~0.2 G

Figure 7. A Space Station "Train" or "Parade"

TABLE 2

POSSIBLE SPACE STATION EVOLUTION 9OVERLAPPING STEPS)

1. Stockpile resources while developing hardware
2. Use resources as needed, assemble structures, test.
3. Use tether deployer to enhance S.T.S. throughput.
4. Add, test, and use habitation capabilities.
5. Add user payloads and more power.
6. Separate into co-orbiting structures (wagon train).
7. Materials processing on surplus E.T. components.
8. Assembly of deep-space expedition vehicles (=S.S.+deltaV+redundancy)
9. Advanced launch vehicles (single-stage-to-tether)

TABLE 3

NOTES ON "TRAIN" CONCEPT

1. DRAG-MAKEUP IS BY ELECTRODYNAMIC TETHER. (TIMED TO MAINTAIN OR ALTER FORMATION AS DESIRED)

2. STABLE LINE-OF-SIGHT CONFIGURATION AIDS:
    a. Navigation
    b. Communication
    c. Microwave power transfer
    d. Damage Assessment and relief

3. ISOLATION PLUS CONVENIENT ACCESS AIDS:
    a. International programs (maximum autonomy)
    b. Proprietary ventures
    c. Investment protection against hazardous activities

4. TETHER-CLIMBING AND GRABBING "MONKEY" SIMPLIFIES DOCKING

In view of the emerging interest in tethers, the concept of the tether "string" needs serious consideration from a concept/design standpoint. Figure 8 illustrates one approach that would provide multiple redundancy.

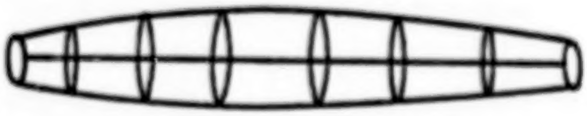


Figure 8. Safety

IV. EARLY CONSTELLATION ACTIVITIES

Both analytical studies/simulations and flight experiments intended to gain background information on constellations were discussed.

Early Constellation Studies and Experiments

- Update dynamic models and control laws for nearly equal masses.
- Numerical study and analysis on drag stabilization and its role in constellations.
- Mass attachment and motion along gravity-gradient stabilized tether - Figure 9.
- Drag stabilized constellation demonstration - Figure 10.
- Rotation-stabilized constellation demonstration - Figure 11.

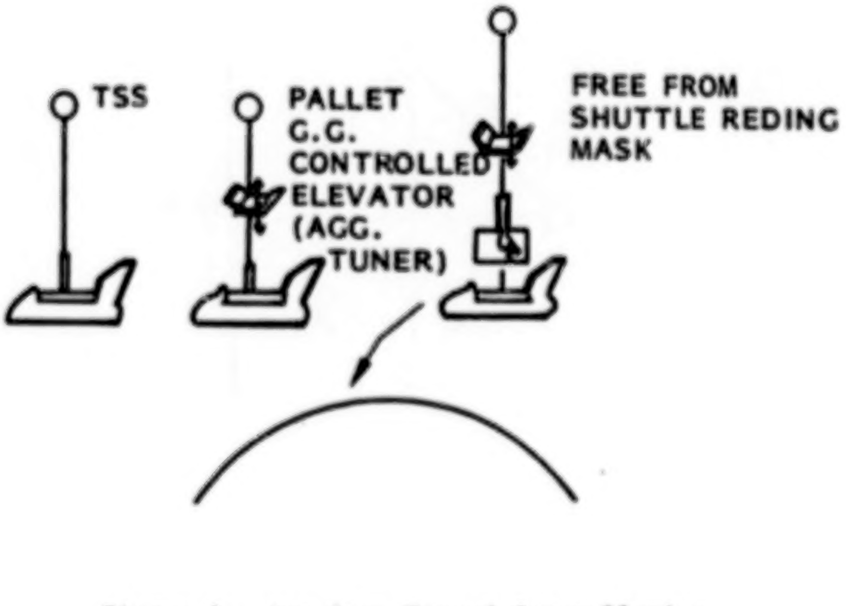

TSS
PALLET
G.C.
CONTROLLED
ELEVATOR
(AGG.
TUNER)
FREE FROM
SHUTTLE REDING
MASK

Figure 9. 1st Step Toward Constellation

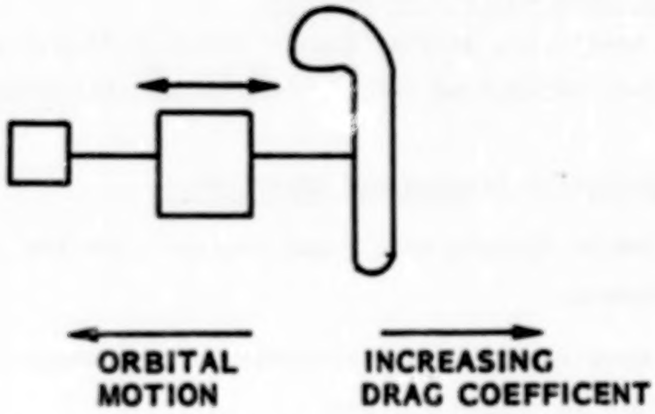

ORBITAL MOTION
INCREASING DRAG COEFFICENT

Figure 10. Drag Stabilized Constellation

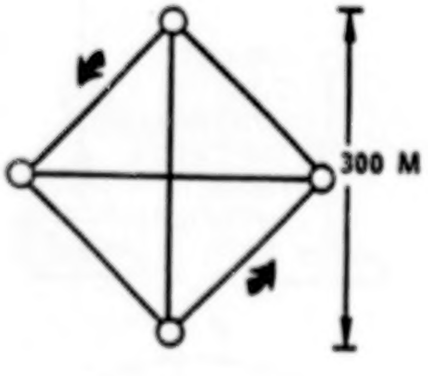


Figure 11. Rotation-Stabilized Constellation

N85-20369

V. PRESENTATION MADE TO THE PANEL

SOME ASPECTS OF ATTITUDE STABILITY OF TETHERED SPACE STATIONS.

S. BERGAMASCHI*

ABSTRACT

In this preliminary investigation the stability of attitude motion of space stations composed by platforms connected by tethers is studied.

The motion is assumed to be three dimensional and the station rigid. First, the well known linearized theory is adopted and the location of different configurations in the stability chart is found; second, a destabilizing feature of finite amplitude motion is outlined as a function of inertia parameters.

---

* Institute of Applied Mechanics.University of Padua.Italy.

INTRODUCTION

Purpose of this report is to focuse some aspects of the attitude dynamics of large tethered space stations, with particular attention to their stability. In fact, the general problem to study the orbit-attitude dynamics of tethered systems is very intriguing, so that it appears reasonable, in this very preliminary stage of definition of such systems, to try to reach a better understanding of some partial aspects which seem to be critical.

One of the reasons of the difficulty of the general problem is that often the specialized literature is not too helpful. This is mainly due to two causes:

a) some aspects of the problem are completely new;

b) the dimensions of tethered systems (in particular in the direction of the local vertical) cause the numerical applications made in previous studies to be not applicable in this case.

The most important of the new features is certainly due to the peculiar properties of tethers, if considered as structural elements. In fact, the inability to resist bending moments or compressive stresses is a severe limitation for design and the problem of attitude stability is more critical than in conventional spacecrafts. It seems also that sometimes this problem has been overlooked; in fact, some constellations have been proposed (at least in the form of artist's conceptions) the stability of which is not clear, if specific assumptions are not made on the elastic properties of some components. In any case, the possibility of using also long structural components resisting to compression must be studied in order to ensure that the form of the station cannot change under the action of perturbations.

One of the main problems belonging to group b) is the coupling between orbit and attitude dynamics. When the size of a spacecraft can be considered as negligibly small in comparison with the semimajor axis of its orbit, the usual assumption is made that, while its attitude is dependent on the orbit, the converse is not true, i.e. orbital parameters are independent from the motion around the center of mass. However, the interaction between attitude librations and orbital motion of a rigid body has been investigated in [1]. The results show that periodic interchange of energy can occur if the pitch frequency is sufficiently close to the mean orbital motion. As it will be shown in the following, this is not the case of bodies elongated in the direction of the local vertical; however the magnitude of the coupling depends on the ratio between the pitch moment of inertia per unit mass and the square of the semimajor axis. Now, in the case of tethered stations, this ratio can easily exceed 10^{-5}, being thus some orders of magnitude larger than the values considered in [1]. Therefore, it cannot be excluded a priori that, even if far from eccentricity resonance, large tethered systems should not suffer from orbit-attitude coupling.

As a consequence of the considerations made above, the analysis here-after is intended to investigate the attitude stability of tethered stations similar to the asymmetric systems proposed in [2] and shown in Fig.1. The following restrictive assumptions are inherent in the model:

- the geometric shape of the station cannot change, i.e. it can be treated as rigid. This is the reason why only very asymmetric systems are taken into account, which seem to be more stable than symmetric stations built up with equal platforms. Accordingly, it will be assumed that the dimensions of one of the decks are much larger than those of the other;
- orbit dynamics is independent from attitude motion; moreover Earth's oblateness and other perturbing effects are neglected.

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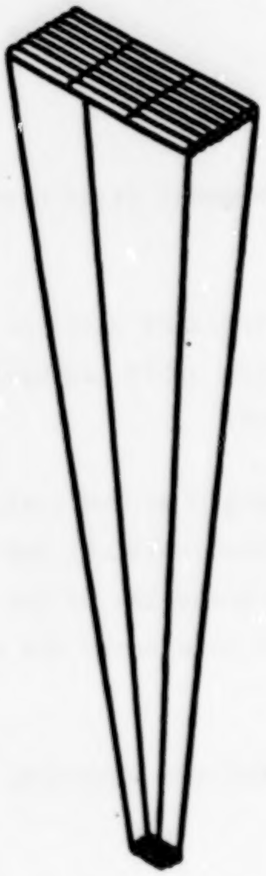

FIGURE 1.-

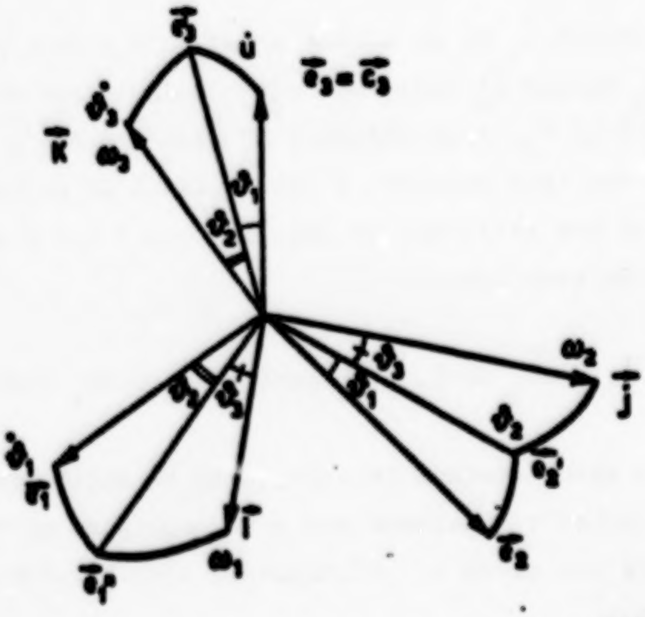
$\vec{e}_3$
$\dot{u}$
$\vec{e}_3 = \vec{e}_3$
$\dot{\vartheta}_3$
$\vec{K}$
ω_3
ϑ_1
ϑ_2
ω_2
ϑ_3
ϑ_1
$\vec{j}$
$\dot{\vartheta}_2$
$\vec{e}_2'$
$\vec{e}_2$
ϑ_2
ϑ_3
$\dot{\vartheta}_1$
$\vec{e}_1$
$\vec{i}$
ω_1
$\vec{e}_1'$

FIGURE 2.-

C-3

THE MATHEMATICAL MODEL

Let us consider three orthogonal right-handed references:

- system $(\vec{c}_1, \vec{c}_2, \vec{c}_3)$ with $\vec{c}_1$ coincident with the direction of the ascending node of the station orbit (assumed to be fixed) and $\vec{c}_3$ normal to the orbit plane;
- system $(\vec{e}_1, \vec{e}_2, \vec{e}_3)$ with its origin at the station center of mass, $\vec{e}_1$ along the ascending local vertical and $\vec{e}_3 = \vec{c}_3$. Note that $\vec{e}_2$ is coincident with the direction of the orbital velocity only when the station path intersects tha apsidal line or if the orbit is circular;
- system $(\vec{i}, \vec{j}, \vec{k})$, coincident with the principal axes of inertia of the station.

As usual, systems $(\vec{e}_1, \vec{e}_2, \vec{e}_3)$ and $(\vec{i}, \vec{j}, \vec{k})$ can be brought in coincidence by means of three counterclockwise rotations, defined as follows (see Fig. 2):

first rotate around $\vec{e}_1$ by an amount equal to θ_1; then perform a rotation of θ_2 around $\vec{e}\,'_2$ bringing $\vec{e}\,'_3$ in coincidence with $\vec{k}$; last, rotate around $\vec{k}$ by θ_3, thus aligning $\vec{e}\,''_1$ with $\vec{i}$ and $\vec{e}\,'_2$ with $\vec{j}$. Let now f denote the true anomaly, ω the argument of perigee and u the argument of the latitude, so that $u = \omega + f$ and $\dot{\vec{u}} \approx \dot{f}\,\vec{c}_3$; then it can easily be seen that:

$$(1) \qquad \dot{f} = -\dot{\theta}_1 \cos\theta_1 \sin\theta_2 + \dot{\theta}_2 \sin\theta_1 + \dot{\theta}_3 \cos\theta_1 \cos\theta_2$$

If the space station is assumed to be rigid, the governing equations are Euler's equations and the components of the gravity gradient torque are given in [3] together with the transformation of system ($\vec{i}, \vec{j}, \vec{k}$) into ($\vec{c}_1, \vec{c}_2, \vec{c}_3$). Thus, the equations of motion can be written in terms of the unknowns θ_1, θ_2, θ_3.

THE LINEARIZED EQUATIONS

If it is assumed that the eccentricity of the orbit is small, only the linear terms can be retained in the power series developments of $\dot{f}$ and r as functions of the mean anomaly, so that:

$$(2) \qquad \dot{f} = n(1+2e \cos nt) \qquad r = a(1-e \cos nt)$$

Moreover, if only small angular motions are investigated and products $e \cdot \theta_i$ $(i=1,2,3)$ are neglected, the equations of motion can be linearized and the well known result is that the pitch motion is uncoupled from roll-yaw and that some conditions have to be fulfilled by the principal moments of inertia, in order to ensure stability [4]. In fact, if:

$$(3) \qquad k_1 = \frac{I_3-I_2}{I_1} \qquad k_2 = \frac{I_3-I_1}{I_2} \qquad k_3 = \frac{I_2-I_1}{I_3}$$

the equation of motion are:

$$(4) \qquad \begin{aligned} &\ddot{\theta}_1 + k_1 n^2 \theta_1 + n(k_1-1)\,\dot{\theta}_2 = 0 \\ &\ddot{\theta}_2 + 4k_2 n^2 \theta_2 + n(1-k_2)\,\dot{\theta}_1 = 0 \\ &\ddot{\theta}_3 + 3k_3 n^2 \theta_3 = 2\,n^2 e \sin nt \end{aligned}$$

and the stability chart is shown in Fig.3.

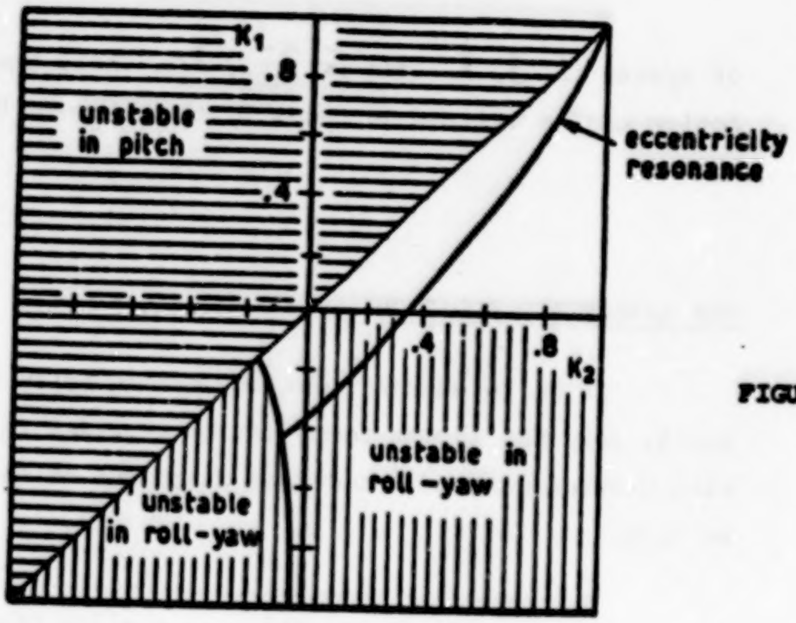

FIGURE 3.-

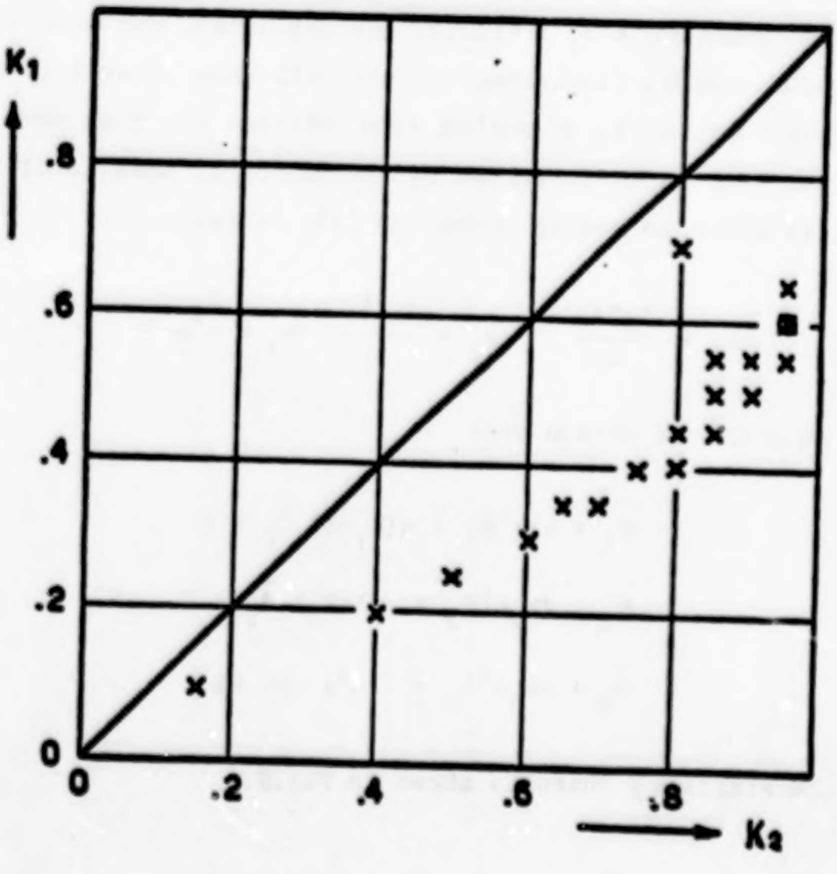

FIGURE 4.-

A feature common to all the space stations dealt with in this report is to be elongated in the direction of the local vertical, so that $I_3 > I_2 \gg I_1$; therefore, the interesting portion of the stability chart is reduced to the lower half of the first quadrant. To be more specific, let us consider the asymmetric arrangement shown in Fig.1 ; ℓ is the distance between the decks, a_i and b_i the dimensions in the direction of the roll and pitch axes, respectively. If the decks are assumed to be rectangular, the inertia ratios are found to be:

$$k_1 = \frac{m_1(a_1^2 - b_1^2) + m_2\ (a_2^2 - b_2^2)}{m_1(a_1^2 + b_1^2) + m_2\ (a_2^2 + b_2^2)}$$

$$k_2 = \frac{M\ell^2 - (m_1b_1^2 + m_2b_2^2)/12}{M\ell^2 + (m_1b_1^2 + m_2b_2^2)/12} \tag{5}$$

$$k_3 = \frac{M\ell^2 - (m_1a_1^2 + m_2a_2^2)/12}{M\ell^2 + (m_1a_1^2 + m_2a_2^2)/12}$$

where $k = m_1m_2/(m_1+m_2)$ is the reduced mass of the system. Let us now assume that the upper platform is built up by assembling 24 External Tanks, that the lower one is composed by 3 E.T. and that their distance is $\ell = 45$ km. Then, the pertinent figures are:

$m_1 = 600$ tons $\qquad m_2 = 75$ tons

$a_1 = 150$ m $\quad b_1 = 64$ m $\quad a_2 = 50$ m $\quad b_2 = 24$ m

(The values above are consistent with those reported in [2]).

In this case:

$k_1 = 0.691 \qquad k_2 = 1 - 0(10^{-6}) \qquad k_3 = 1 - 0(10^{-5})$

and it is clearly understood that the feature $k_2 \approx k_3 \approx 1$ is common to every elongated space station, because, in any case $\ell >> a > b$. Thus, it can be seen that the points representative of tethered space stations in the diagram of Fig.2 lie almost exactly on the vertical segment defined by $k_2 = 1$ and $0 < k_1 < 1$. In fact, while k_2 can differ from unity only by negligibly small amounts, k_1 can easily be changed by changing the ratio a/b in the larger platform. In any case, the motion appears to be stable and its feature can easily be investigated. The pitch motion is given by:

$$\theta_3(t) = A \cos n\sqrt{3}t + B \sin n\sqrt{3}t + e \sin nt$$

so that no problem is expected to arise from eccentricity resonance. Putting: $\theta_i = a_i e^{st}$ in the first two of eqs.(4), the determinantal equation is:

$$(6) \qquad \begin{vmatrix} s^2 + k_1 n^2 & n(k_1-1)\, s \\ n(1-k_2)\, s & s^2 + 4k_2 n^2 \end{vmatrix} \approx \begin{vmatrix} s^2 + k_1 n^2 & n(k_1-1)\, s \\ 0 & s^2 + 4 n^2 \end{vmatrix} = 0$$

from which it is seen that the roll motion is almost completely decoupled from yaw and its frequency is equal to 2n. On the contrary, two harmonic components are present in yaw, the first with frequency $\omega_1 = n\sqrt{k_1}$ and the second with $\omega_2 = 2n$. In the case of the example above, the general solution is:

$$(7) \qquad \begin{aligned} \theta_1(t) &= A_1 \sin(0.831\ nt + \phi_1) + A_2 \sin(2\ nt + \phi_2) \\ \theta_2(t) &= 5.355\ A_2 \cos\ (2\ nt + \phi_2) \end{aligned}$$

LIBRATIONS WITH FINITE AMPLITUDE

The picture outlined in the preceding paragraph is altered if finite amplitude librations are taken into account.In accordance with the analysis of Kane [3], let us consider the space station to follow a circular path; this assumption is now not too restrictive,because it has been shown that the points representative of tethered systems in Fig.3 can easily be located sufficiently far from the curve representative of eccentricity resonance. Thus, if the equations of motion are not linearized, n is substituted for $\dot{f}$ and the resulting differential system is integrated, the following features of attitude motion can be found:

1) the dynamics are intrinsically three-dimensional; i.e. incorrect results can be deduced if only the in-plane component of motion is considered. This is because it may occur that a "small" initial in plane component of the motion causes the out of plane component to librate with slowly varying amplitudes, so that it is possible that, after some ten orbital periods, the angle between the pole of the orbit and the pitch axis is as large as 0.25 rad.

   It is also noted that in this context "small" means amplitudes which are generally well below the limits of the linear theory, i.e. 1°;

2) the stability chart must be modified. In fact, the feature mentioned above depends both on the amplitude of the in plane motion and on the values of the inertia parameters k_1 and k_2; as a consequence, part of the region defined as stable in the linearized model is found to be "unstable" (or less stable) in the sense mentioned in 1).

A first indicative results is shown in Fig.4 (taken from [3]), where only the interesting portion of the "stable" area of Fig.3 is reported.

The crosses denote points found unstable by computer integration. The initial amplitude θ_3^* was 5°. It can be seen that the point representative of the numerical example made in the previous paragraph lies in proximity of the boundary of the unstable region. It is also noted that if θ_3^* is reduced to 1°, the area marked by crosses is significantly smaller, but the point with a circle around the cross is still unstable. To find the implications of this analysis on the form of the decks of the station shown in Fig.1, let us assume:

$$(8) \qquad \frac{m_2(a_2^2 - b_2^2)}{m_1(a_1^2 - b_1^2)} \ll 1 \quad \text{and} \quad b_1 = \alpha a_1 \quad (0 < \alpha < 1)$$

so that the first of eqs.(5) becomes:

$$(9) \qquad k_1 = \frac{1 - \alpha^2}{1 + \alpha^2}$$

The dependence of k_1 on α is shown in Fig.5, from which it can be seen that if the interval $0.55 < k_1 < 0.65$ is considered to be unstable (it depends on θ_3^*), platforms have to be assembled in such a way that $b_1 < 0.45\ a_1$ or $b_1 > 0.55\ a_1$.

The present investigation has to be considered a very preliminary one. As further steps first the maximum allowable θ_3^* for space stations has to be decided; secondly, extensive recourse has to be made to numerical computation in order to define sharply the limits of the unstable region when $k_2 \approx 1$; third, the different dynamical features of the motion of elongated vs. quasi square stations has to be investigated. Further, the effect of orbit eccentricity can be included in the model.

The particular configuration shown in Fig.1 must be considered just as an example. In fact much effort must be concentrated to design statically stable configurations. In this context, it might be that the two platforms of Fig.1, rigidly coupled at a distance of a few km or less, will constitute a subsystem of a larger constellation.

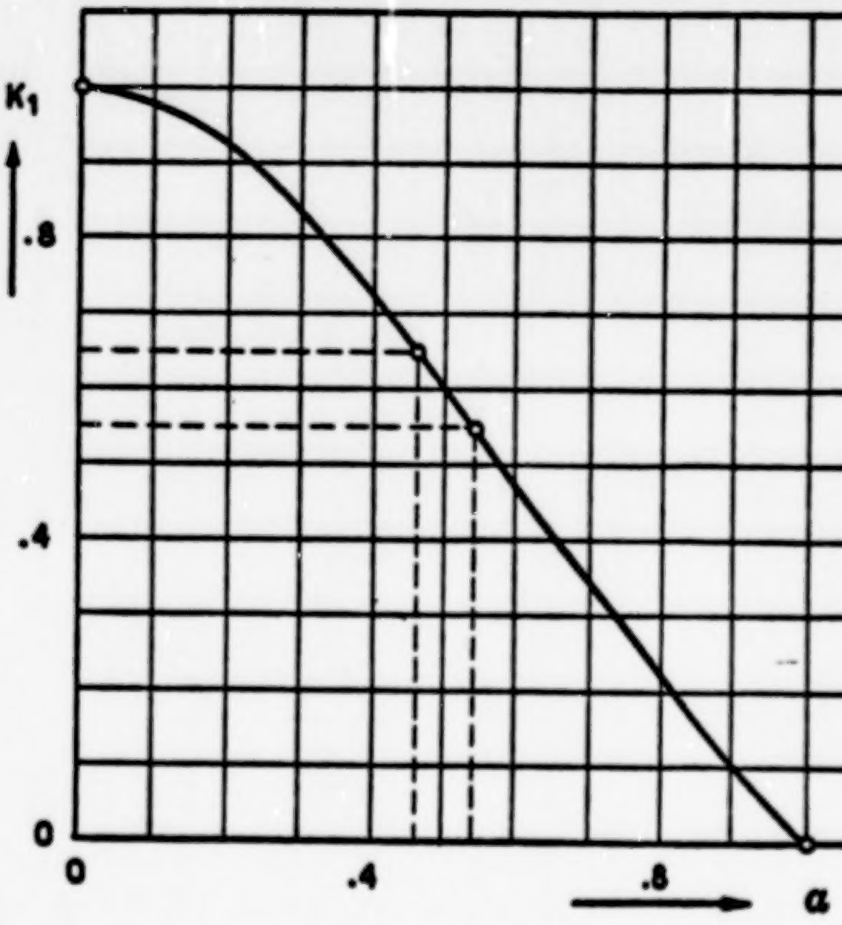

FIGURE 5.-

REFERENCES

[1] Mohan S.M. et al.	"Interaction between Attitude Libration and Orbital Motion of a Rigid Body in a Near Keplerian Orbit of Low Eccentricity".Celestial Mechanics,5, 1972
[2] Colombo G.,Slowey J.	"A New Tethered Dual Platform Concept". S.A.O. Interim Progress Report.Contract G 82678-3286,January 1983
[3] Kane T.R.	"Attitude Stability of Earth-Pointing Satellites". AIAA Journal,Vol. 3, n.4, April 1965
[4] Kaplan M.H.	"Modern Spacecraft Dynamics and Control", Ch.5, J.Wiley and Sons, 1976

N85-20370

REPORT OF THE
TECHNOLOGY AND TEST PANEL

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TECHNOLOGY AND TEST PANEL

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Harold Compton	NASA/LARC
Roy J. Duckett	NASA/LARC
Carlo Buonjiolno	PSN/Italy
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TECHNOLOGY AND TEST

The tasks accomplished by the Technology and Test panel were three: (1) Review the state of technology relative to the Tethered Satellite System (TSS), (2) Define the technology areas which could benefit from the TSS, and (3) Define the technology and test support required by other TSS applications. During the workshop two technology issues dominated the deliberation in the T&T panel. These issues were tether material and dynamic modeling technology. The former, tether materials, was by far the dominant concern of the T&T panel, it was also a significant concern of the Transportation and Electrodynamics panels. Although, it was agreed that the immediate problem associated with the tethers for the 20 km electrodynamic and 100 km atmospheric missions could be solved--engineering design fixes--it is recommended that an extensive materials development program be initiated to develop the tethers required to support the application being defined.

To support TSS design studies it is necessary to develop tether dynamic model computer codes for definition of mission and tether requirements. Present major codes are very elaborate, expensive to run, and not very user friendly-this technology concern is being addressed by the existing Tether Dynamic Working Group. (See Section II for Presentation). The recommendations from this group which should be available for review later this year should be quickly evaluated and implemented to support program development and tether application feasibility studies which will be key elements in the definition of future technology development programs.

An additional technology concern was related to the manufacturing of tethers. The development of complex tethers (nonconducting-taper/double taper long >100 km, conducting - embedded conduction, fiber optics; super conducting, etc.) and their application to space stations requires the development of manufacturing capabilities for both Earth-based as well as space-based systems. (See Section III for Presentation.)

Application No. 1 - Tethered "Wind-Tunnel"

The interest of the majority of the participants in the T&T panel was related to the use of the TSS to conduct atmospheric and aerothermodynamics related research. The TSS can provide access to that part of the atmosphere which is presently probed only briefly by rockets and reentry vehicles. The use of the TSS as a "wind-tunnel" would provide the capability to define the upper atmosphere and its variations as well as provide data relative to rarefied gas dynamics (free molecule, slip and transition flows) required in the design of advanced STS, TAV, aerobraking and aero-assisted vehicles. Such a system could provide the pressure, loads and heating data required and not presently available from ground facilities.

The data would also allow the development and verification of analysis codes required in the vehicle design process.

This program is of particular interest to: LaRC personnel, Paul M. Siemers, Harold R. Compton, Roy C. Duckett, and Ken Sutton, University of Dayton personnel N. Engler and J. Luers, G. Carlomagno of the University of Naples and C. Buongiorno, University of Rome/PSN.

Preliminary data from each application is included in Section III.

- A critical supporting technology relative to this application is the definition and development of the instrumentation required. Such activity is proposed by G. Wood, LaRC. (See Section III.)

Many concepts were presented and discussed - each deserving of additional studies - concepts incorporated baseline satellite (Phase I), modified baseline satellites (Phase II), mission peculiar configurations and combination concepts incorporating and demonstrating tether operations, tether separation dynamics, entry, and verification of deboost/reboost concepts.

Application No. 2 - Large Aperture Antenna Range, W. Grantham, LaRC

Studies have indicated that the use of a tether system for Large Aperature Antenna calibration was not competitive with using the TDRSS. This application cannot therefore be recommended.

Application No. 3 - Vehicle Attitude Control, Ron Mullen, GSFC

Application No. 4 - Orbital Wake Effects, D. Potter, JSC

Application No. 5 - Power General-Multiple Tether, D. Renz, LeRC

Application No. 6 - Tether Space Station Modules, J. Price, Kentron/LaRC

- Emergency habitat/rescue modules
- Hazardous storage

Application No. 7 - Test - Utilize Gemini deployments station keeping techniques demonstration of concept using orbiter and ET, Dean Monitor Martin, Marietta, Michoud.

The tether application proposed by the Technology and Test panel were all judged to be feasible and practical. In addition in each case where data is the product the ability to obtain such data does not presently exist - the tethered wind tunnel being the prime example. The need for in situ data dictates a flight system. The need for this flight system dictates the need for tethers which then dictates the need for materials and dynamic model code development programs. The development of these two technologies will dictate the pace of tethered system evolution. Tables 1 through 4 summarize key issues in: Dynamics, Guidance and Control; Material Degradation; Satellite Tracking; and Remote TSS Operation.

TABLE 1

DYNAMICS AND GUIDANCE AND CONTROL

a. There are today a large number of orbital mechanical models, all differing in some respects: rigid tethers, inextensible tethers, drag, distributions of the mass of the tether and of the satellite, etc.

b. What is needed, and is being developed, is an engineering dynamics model. Such a model will be sufficiently accurate for many purposes, e.g. mission timelines.

c. Such a model will also be used extensively for the development of "standard" control algorithms.

TABLE 2
MATERIAL DEGRADATION DUE TO ATOMIC OXYGEN

a. Three Kevlar samples were flown on the STS-5, each maintained at a different temperature.

b. These three samples were not under tight control, e.g. no clear room procedure, handled by various people, etc. The reason for this was there was very little time available.

c. These three samples were subjected to break strength tests, and compared to five samples (from the same lot number) which weren't flown.

d. Using non-parametric tests, there is about one chance in sixty that the lower breaking strength of the three flown samples was a random fluctuation. Therefore we have concluded that the strength of the flown samples was decreased.

e. We don't know at the present time what caused this decrease. Scanning electron microscope photographs show that the exposed Kevlar surfaces have an eroded appearance. Blame has been placed on atomic oxygen.

f. We have several samples of different materials, Kevlar included both bare and coated, which will be flown on STS-8.

g. Even if Kevlar 29 is degraded, its diameter can be increased so that adequate strength with a generous margin of safety for a 36 hour mission can be achieved.

h. MSFC and Martin Marietta are presently conducting an exhaustive series of tests on Kevlar, subjecting it to UV, thermovac, and atomic oxygen.

TABLE 3
TRACKING

a. At the present time, we do not have a tracking system that is entirely suitable for position and rate determination of the satellite from the orbiter.

b. It can be done using the Orbiter's Ku-band radar, but this requires extensive interfacing with the Orbiter system, a situation that is best avoided.

c. At the present time we are developing a tracking system for the TSS, one that will probably consist of a dedicated TSS radar on the Shuttle and a transponder on the satellite.

d. The satellite does not need to be tracked at a very high data rate: the position of the satellite does not change randomly, and the use of a good computer dynamics model should allow acceptable position determination from a relatively low radar repetition rate.

e. If a low refs. rate is used, then it ought to be possible to use a relatively powerful radar—to improve its ranging capability—and still not require an inordinate amount of energy for its operation, on the average. (I am told that the Orbiter's Ku band could be a much better radar, if operated at higher levels.)

TABLE 4
REMOTE TSS OPERATION

a. The context of the TSS has been generally that of a tethered satellite released from a manned mothership.

b. If a tethered satellite is released from an unmanned spacecraft, some of the problems are accentuated.

c. One of these, for example, would be the entire guidance and control of the satellite from ground stations.

d. If it is assumed that the tethered system is one that, say, is doing an atmospheric mission on the venusion atmosphere, we need a completely automated system: the time of transmission makes timely human inputs infeasible.

e. Of course, the materials problem will be aggravated tremendously.

II. TETHERED SATELLITE MODELING STATUS

TETHER DYNAMICS WORKING GROUP
QUESTIONNAIRE FOR TETHERED SATELLITE SOFTWARE

1. General Information

Name of Program SKYHOOK
Version/Date III/1982 ☐ new ☒ revised
Current Author David A. Arnold
Phone (617) 495-7269
Author's Affiliation SAO
Address 60 Garden St., Cambridge, MA 02138
Submitter (if different)
Phone
Submitter's Affiliation
Address
Is Maintenance Available? ☐ yes ☒ no
Consultation ☒ yes ☐ no
Person to Contact David A. Arnold
Phone see above

2. Program Description

(include features modelled; e.g. airdrag, three dimensional motion, orbital assumptions, tether mass assumptions, end mass rotation, etc.)

SKYHOOK models tether as discrete lumps and does numerical integration in Cartesian co-ordinates. Forces modelled are:

Dynamical

- Terrestrial gravity field
- Full Gravity Anomally Model
- Solar and Lunar Gravitation
- Atmospheric Drag
- Solar Radiation Pressure
- Earthshine Radiation Pressure
- Tidal Forces
- Subsatellite Attitude Control Forces

Thermal

- Solar Radiation Heating
- Atmospheric Drag
- Radiative Cooling

Mechanical

- Linear Stress/Strain
- Thermal Expansion
- Viscoelastic Damping
- Arbitrary Control Laws

Electrodynamic

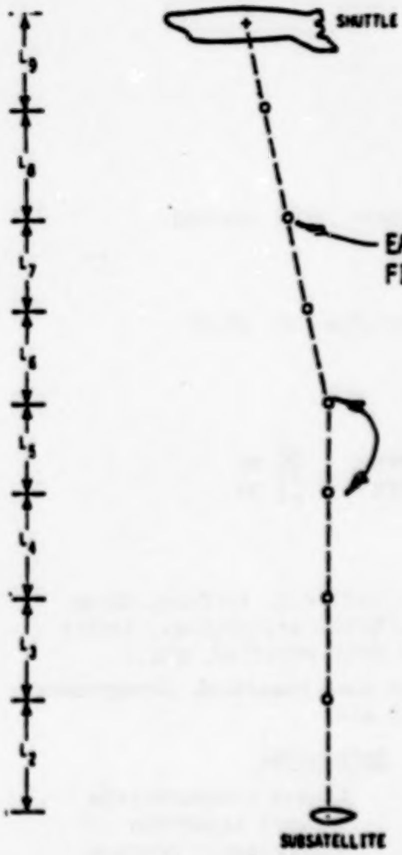
- Earth's Magnetic Field
- Electric Field
- Charge Collection

3. Modelling & Numerical Methods:

Each mass point is assigned the physical characteristics of a finite length tether segment. Mass point interactions determined by a set of coupled differential equations which are numerically integrated to calculate system behavior.

N-MASS POINT REPRESENTATION OF A TETHER
(N=20 MAXIMUM IN PRESENT SOFTWARE)

SKYHOOK



EACH MASS POINT HAS PHYSICAL CHARACTERISTICS OF FINITE LENGTH TETHER SEGMENT

MASS POINT INTERACTIONS DETERMINED BY A SET OF COUPLED DIFFERENTIAL EQUATIONS WHICH ARE NUMERICALLY INTEGRATED TO CALCULATE SYSTEM BEHAVIOR

NO RESTRICTIONS ON MECHANICAL, THERMAL, ELECTRICAL, OR BULK CHARACTERISTICS OF ANY TETHER SEGMENT

NO RESTRICTIONS ON INITIAL CONDITIONS REPRESENTING ECCENTRICITY OR ORIENTATION OF SHUTTLE ORBIT

13 OCTOBER 1982

TETHER DYNAMICS WORKING GROUP
QUESTIONNAIRE FOR TETHERED SATELLITE SOFTWARE

4. I/O Requirements

What are the inputs?

SKYHOOK requires initial conditions (e.g., $V_x, \dot{V}_x, \ddot{V}_x$) for each mass point. DUMBEL is used as a pre-processor to calculate these initial conditions at system equilibrium from fundamental system parameters (e.g., mass of orbiter, tether mass, orbital height). Inputs are described in detail in references 1 and 2.

What are the outputs?

☒ Batch or ☒ Interactive

Graphics? ☒ yes ☐ no

For each mass point as a function of time SKYHOOK provides:

Cartesian co-ordinates
Tension
Current
Displacement
Temperature
Voltage

and dynamic plots of behavior as a function of time:

In-plane Motion **Out-of-Plane Motion** **Radial Motion.**

5. Limitations, Restrictions, Deficiencies, Problems -

20 mass points maximum in existing software.

- need to evaluate desirability for more computational time

6. Extras

- Was the program explicitly written to make it transportable? **Yes**
- Are there special arithmetic precision requirements (beyond 32-bit/7-digit floating point)? **Yes - 15 digits required**
- In what format can you make this program available? (e.g., punch cards, magnetic tape, etc.). **magnetic tape**

TETHER DYNAMICS WORKING GROUP

QUESTIONNAIRE FOR TETHERED SATELLITE SOFTWARE

7. Operating System Information

Computer(s) and operating system(s) on which this program is currently operating:

Primary System (on which program was developed/is maintained):
DIGITAL EQUIPMENT CORPROATION VAX

Other systems (to which program has been transported).

Has been modified to run on Sigma 5 at MSFC. Other machines not known.

Source Code Languages
(e.g., Algol 60, Fortran IV, Assembly Code): FORTRAN IV

Does the source conform to applicable standards (e.g., ANSI) or does it use a superset of the standard language ("extra features")?

Core Memory Required:

Peripherals Required:

Standard DEC Tape and Disk Drives

Special Hardware Required (beyond minimum for operating system; e.g., graphics terminals, etc.) Versatec Plotter for Graphics.

Are these requirements innate to the purpose of the program, or might they be avoided with some re-programming? Program is adaptable to other systems by reprogramming. Two dimensional plotter required for wire configuration display.

Other Software Needed:

- Standard (e.g., routines from math libraries): -

DEC Math Library

- Parallel (i.e., are there any non-standard programs which must be run in parallel with this program.)

None

TETHER DYNAMICS WORKING GROUP
QUESTIONNAIRE FOR TETHERED SATELLITE SOFTWARE

- Required Pre- and Post-Processors

A preprocessor called DUMBEL is generally used to generate initial conditions and various post-processors are used to analyze and plot the output. These summarized on the attached sheets.

- Optional (e.g., a display program)

None

8. Related Publications and Write Ups.

1. "Study of the dynamics of a tethered satellite system (SKYHOOK)," Kalaghan et al., Final Report Contract NAS8-32199, March 1978.
2. "The Skyhook Program: A software package for a tethered satellite system, including electrodynamic interactions," L.R. Kirschner, Technical Report Contract NAS8-33691, May 1980.
3. "Study of tethered satellite active attitude control," G. Colombo, Contract NAS8-33691.

TETHER PROGRAM SOFTWARE SUMMARY
SMITHSONIAN ASTROPHYSICAL OBSERVATORY
PRE-PROCESSORS

DUMBEL- In addition to two-mass integration, DUMBEL computes initial state vectors as a function of the orbital and tether system parameters. Wire mass points are generated at equal intervals along the wire.

EQVILIN- Computes the initial state vector for a tether system allowing the user to specify the mass and location of each mass point.

TETHER PROGRAM SOFTWARE SUMMARY
SMITHSONIAN ASTROPHYSICAL OBSERVATORY
POST-PROCESSORS

GRAPH- Generates Versatec plots of quantities resulting from a SKYHOOK or DUMBEL run. The parameter vs. time options are: Radial Position, In-plane Position, Out-of plane Position, Shuttle and other Tension Values, Temperature, Voltage and Current. Parameter vs. parameter plots are: In-plane vs. Out-of-plane Position and Out-of-plane vs. Radial Position.

PLOTFIL- Generates parameter vs. time plots on the printer page for Radial , In-plane, Out-of-plane distance from Shuttle to subsatellite, Tension for any mass point, Temperature, Current, Voltage, and Spacing between mass point pairs.

PLOTFIL2- Generates parameter vs. time plots on the printer page for the difference between two computer runs of any one parameter.

INIT- Reads the state vectors produced by SKYHOOK or DUMBEL and plots the altitude and velocity of the Shuttle, subsatellite, and center-of-mass of the Shuttle plus subsatellite, vs. time. At a time specified by the user, the program computes the orbital parameters of the center-of-mass, and of the Shuttle and subsatellite on the assumption that they disconnect from the wire at that time. The kinetic potential and total energy of each end mass and the center-of-mass is also computed at the specified time.

CRUNCH2- Condenses a file of plotting parameters by selecting every N^{TH} point.

CRUNCH9- Condenses a file of state vectors by selecting every N^{TH} point.

November 17, 1982

TETHER PROGRAM SOFTWARE SUMMARY
SMITHSONIAN ASTROPHYSICAL OBSERVATORY
DYNAMIC INTEGRATORS

SKYHOOK- MODELS THE WIRE AS DISCRETE LUMPS. DOES A NUMERICAL INTEGRATION IN CARTESIAN CO-ORDINATES. INCLUDES POSITION, VELOCITY, TEMPERATURE, ELECTRIC CHARGE, AND ROTATION OF SUBSATELLITE IN THE INTEGRATION VARIABLES.

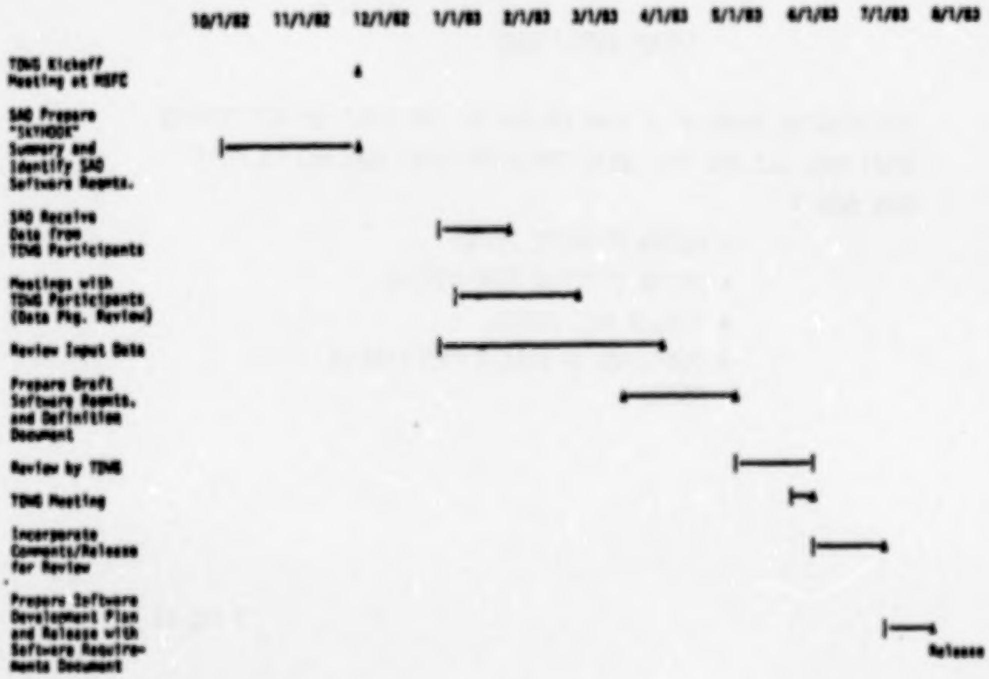
DUMBEL- MODELS THE WIRE AS MASSLESS, SYSTEM WITH TWO MASSES. DOES NUMERICAL INTEGRATION IS CARTESIAN CO-ORDINATES. INCLUDES POSITION, VELOCITY AND ROTATION OF THE SUBSATELLITE IN THE INTEGRATION VARIABLES.

STABLE- MODELS WIRE AS RIGID MASSLESS ROD. ASSUMES SHUTTLE IN A CIRCULAR ORBIT. INTEGRATES THETA, THETA-DOT, PHI, PHI-DOT, R, AND R-DOT OF THE SUBSATELLITE AS A FUNCTION OF TIME. THE VARIABLE R-DOT MAY BE REPLACED BY A RATE CONTROL LAW SO THAT ONLY FIVE VARIABLES ARE INTEGRATED.

WAVES- A "MANY" MASS MODEL INTEGRATING ONLY THE RADIAL VARIABLE WITH NO GRAVITY FIELD.

ZETAO- INTEGRATES TRANSIENT ELECTRODYNAMIC BEHAVIOR OF WIRE WITH UP TO 40 MASS POINTS. ASSUMES ORBITAL PARAMETERS SUCH AS MAGNETIC FIELD, VELOCITY, AND WIRE CONFIGURATION CONSTANT.

TETHER DYNAMICS WORKING GROUP
SOFTWARE REQUIREMENTS DEFINITION
NAS8-35036



13 DECEMBER 1982

TETHER DYNAMICS WORKING GROUP
SUGGESTED GOALS

PROVIDE A FORUM FOR DISCUSSION OF TETHER DYNAMICS PROBLEMS AND ISSUES

PROVIDE GUIDANCE TO TSS CONTRACTOR AND NASA ON TETHER DYNAMICS ISSUES

TRACK AND DISCUSS TETHER DYNAMICS STUDY RESULTS

REVIEW AND APPROVE CHANGES TO BASELINE DYNAMICS SOFTWARE SET

MEETING FREQUENCY: QUARTERLY, AND/OR AS NEEDED

13 DECEMBER 1982

TETHER SAFETY STUDY

INVESTIGATED BEHAVIOR OF LONG (90-100 KM) AND SHORT (10 KM) TETHERS UNDER REEL JAM AND WIRE BREAK CONDITIONS USING DUAL AND MULTIPLE MASS MODELS.

- MOTION OF ENTIRE SYSTEM
- MOTION OF TETHER NEAR SHUTTLE
- TENSION WAVE STUDIES
- COMPARISON OF RESULTS FROM VARIOUS MODELS

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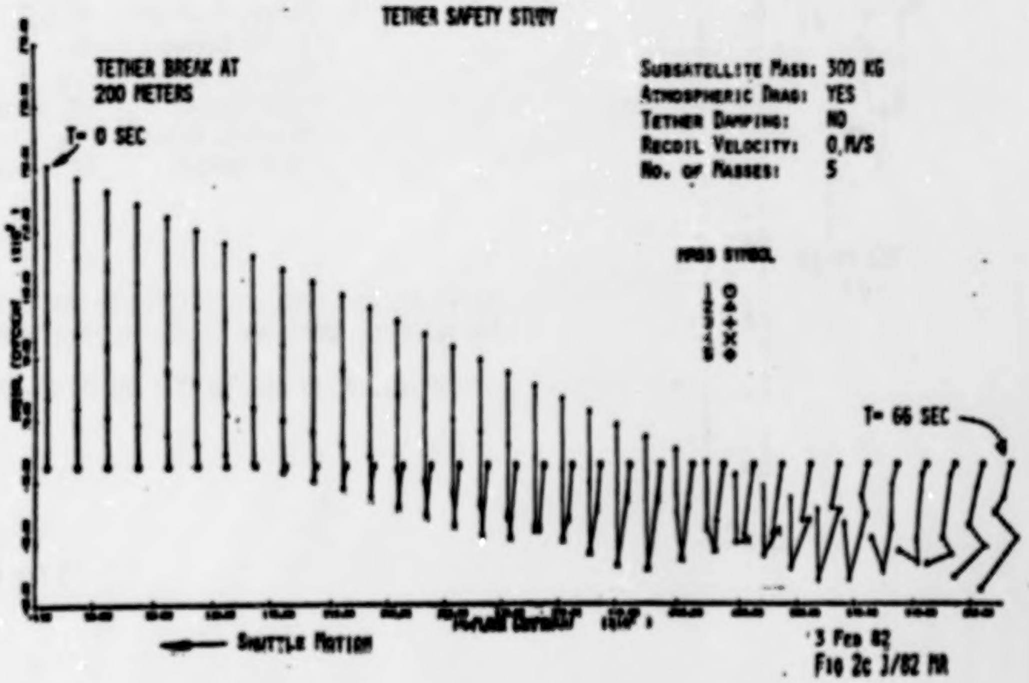

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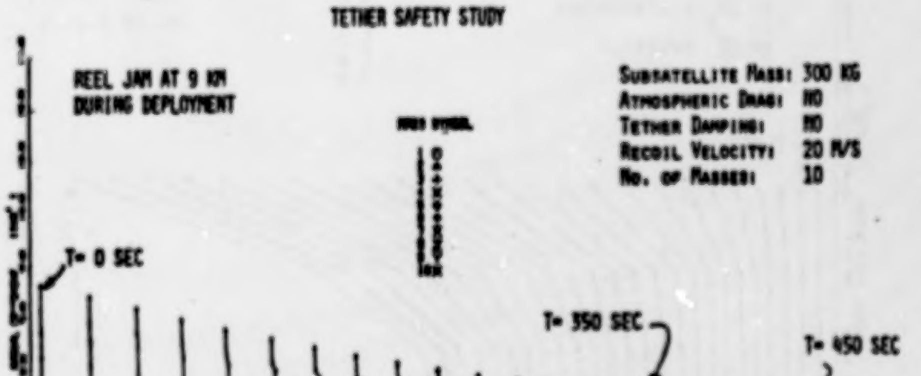
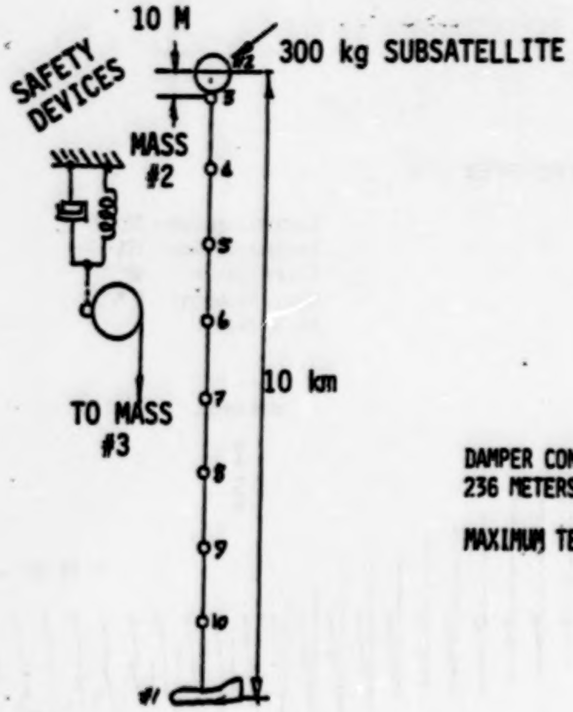


3 Feb 82
Fig 5 11/81 MR

TETHER SAFETY STUDY


10 M
300 kg SUBSATELLITE
SAFETY DEVICES
MASS #2
#2
3
4
5
6
7
8
9
10
#1
10 km
TO MASS #3

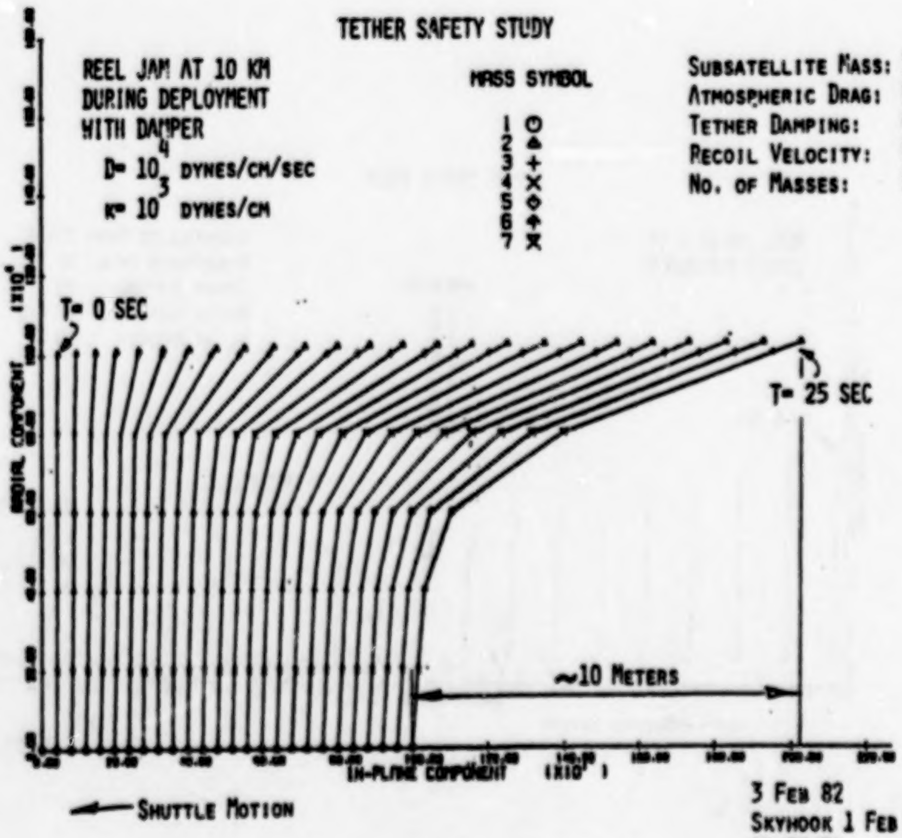
RECOIL CONTROL DAMPER

SUBSATELLITE MASS: 300 KG
ATMOSPHERIC DRAG: NO
TETHER DAMPING: NO
RECOIL VELOCITY: 20 M/S
NO. OF MASSES: 10
DAMPING FACTOR (OF DAMPER): 10^4 DYNES/CM/SEC
SPRING CONSTANT (OF DAMPER): 10^3 DYNES/CM

DAMPER CONTROLS RECOIL COMPLETELY BY DEPLOYING 236 METERS OF ADDITIONAL TETHER IN 23 SECONDS.

MAXIMUM TENSION IS REDUCED BY A FACTOR OF TWO

3 FEB 82



TETHER SAFETY STUDY

REEL JAM AT 10 KM
DURING DEPLOYMENT
WITH DAMPER
D= 10^4 DYNES/CM/SEC
K= 10^3 DYNES/CM

SUBSATELLITE MASS: 300 KG
ATMOSPHERIC DRAG: NO
TETHER DAMPING: NO
RECOIL VELOCITY: 20 M/S
NO. OF MASSES: 7

3 FEB 82
SKYHOOK 1 FEB 82
12:55:51

TETHER SAFETY STUDY

CONCLUSIONS

BEHAVIOR OF WIRE CUT AT 200 M ALSO GIVES BEHAVIOR OF ANY LENGTH OF WIRE UNDER SUDDEN LOSS OF TENSION

TETHER WILL INITIALLY MOVE AHEAD AND BELOW SHUTTLE IN ALL LOSS OF TENSION SITUATIONS WITH SUBSEQUENT BEHAVIOR A FUNCTION OF TETHER LENGTH AND PRESENCE OR ABSENCE OF SUBSATELLITE

BEHAVIOR OF TETHER CLOSE TO SHUTTLE SHOWN IN THIS STUDY IS WORST CASE

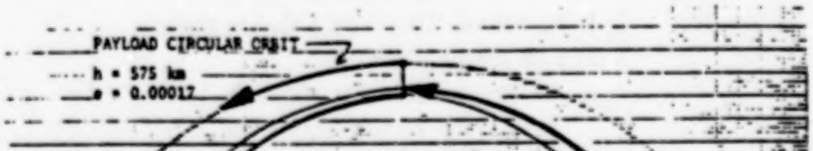
IN A BREAK, TETHER INITIALLY RECOILS AS A UNIT

IN A REEL JAM, SUBSATELLITE INITIALLY MOVES TOWARD AND AHEAD OF THE SHUTTLE

TETHER RECOIL CONTROLLABLE THROUGH A VARIETY OF TECHNIQUES

3 FEB 82
REVISED 7 APRIL 82

PAYLOAD TRANSFER
TO CIRCULAR ORBIT


PAYLOAD CIRCULAR ORBIT
$h = 575$ km
$e = 0.00017$
EARTH
$h_{min} = 165$ km
$h_{max} = 514$ km
$h_{min} = 199$ km
$h_{max} = 519$ km

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PAYLOAD TRANSFER
CONTROL ALGORITHMS

15 JUNE 1983

NATURAL LENGTH OF TETHER IS MODIFIED BY REEL MOTOR ACCORDING TO:

$$L_0(\tau) = L_0 + S(\tau) + \Delta(\tau)$$

PRE-RELEASE REEL MANEUVER: $S(\tau)$

$$S(\tau) \equiv \begin{cases} 0 & \tau < \tau_{START} \\ A \text{ SIN } [2\pi(\tau-\tau_{START})/P-\pi/2] & \tau_{START} < \tau < \tau_{STOP} \\ S(\tau_{STOP}) & \tau_{STOP} < \tau \end{cases}$$

PARAMETERS A, P, τ_{START}, τ_{STOP}

$A > 0$: REEL-OUT INITIALLY

$A < 0$: REEL-IN INITIALLY

USUALLY CHOOSE $\tau_{STOP}-\tau_{START} = P$ OR $= P/2$

ACTIVE DAMPING CONTROL ALGORITHM: $\Delta(\tau)$

$$\begin{cases} \Delta = 0 & \tau \leq \tau_{DAMP} \\ \frac{D}{D\tau}[\Delta(\tau)] = K[T(\tau)-T_0] - B\,\Delta(\tau) & \tau > \tau_{DAMP} \end{cases}$$

WHERE

$T(\tau)$ IS THE PERCEIVED TENSION ON THE REEL

T_0 IS THE NOMINAL (TARGET) POST RELEASE TENSION

K AND B ARE CONTROL PARAMETERS

τ_{DAMP}, THE TIME THE DAMPER IS ACTIVATED, IS NORMALLY THE PAYLOAD RELEASE TIME

OPERATIONAL SEQUENCE

$\tau = 0^s$: SHUTTLE, TETHER, TELEOPERATOR, AND PAYLOAD DEPLOYED IN INITIAL ELLIPTICAL ORBIT

$\tau = 1386^s$: BEGIN PRE-RELEASE REEL MANEUVER:
HALF PERIOD COSINUSOID
A = 182 METERS (REEL-OUT)
P = 150 SECONDS

$\tau = 1441^s$: RELEASE PAYLOAD
INITIATE ACTIVE DAMPER

$\tau = 1461^s$: STOP COSINUSOID MANEUVER

INITIAL ORBIT (CENTER OF MASS):
$H_{MIN} = 199$ KM $H_{MAX} = 519$ KM $E = 0.024$

FINAL ORBIT: SHUTTLE, TETHER, AND TELEOPERATOR
$H_{MIN} = 165$ KM $H_{MAX} = 514$ KM $E = 0.026$

FINAL ORBIT: RELEASED PAYLOAD
$H = 575$ KM $E = 0.0002$

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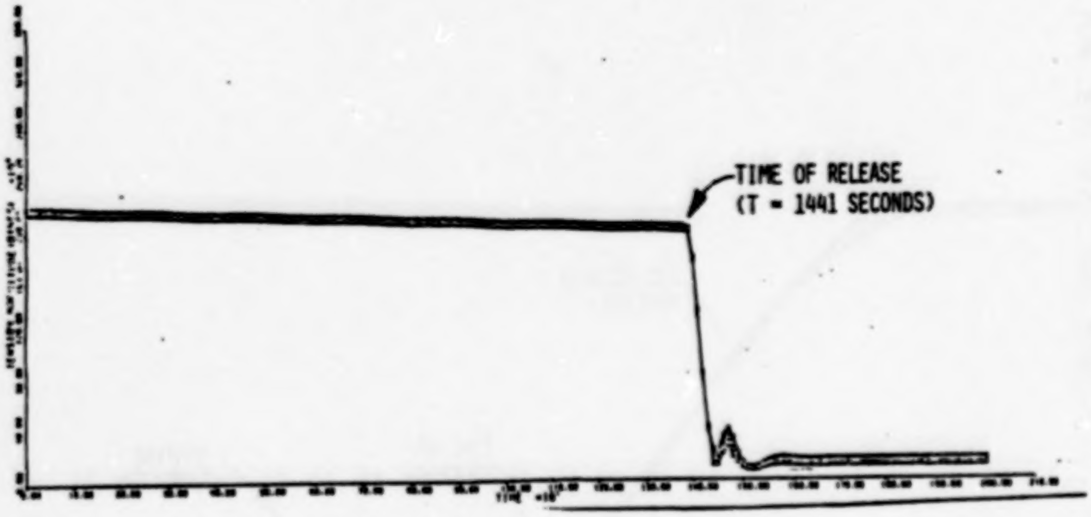
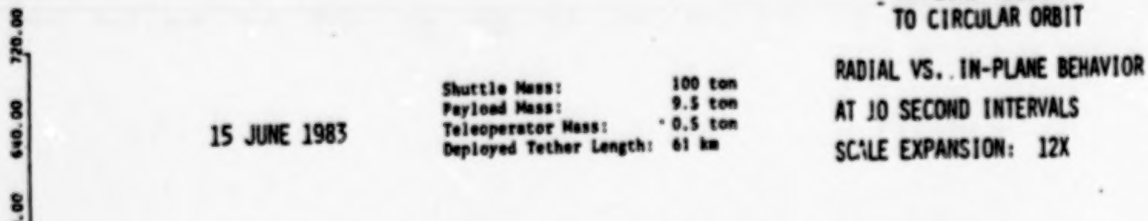
PAYLOAD RELEASE
TO CIRCULAR ORBIT
TENSION VS. TIME

SHUTTLE MASS: 100 ton
PAYLOAD MASS: 9.5 ton
TELEOPERATOR MASS: 0.5 ton
DEPLOYED TETHER LENGTH: 61 km



TIME OF RELEASE
(T = 1441 SECONDS)



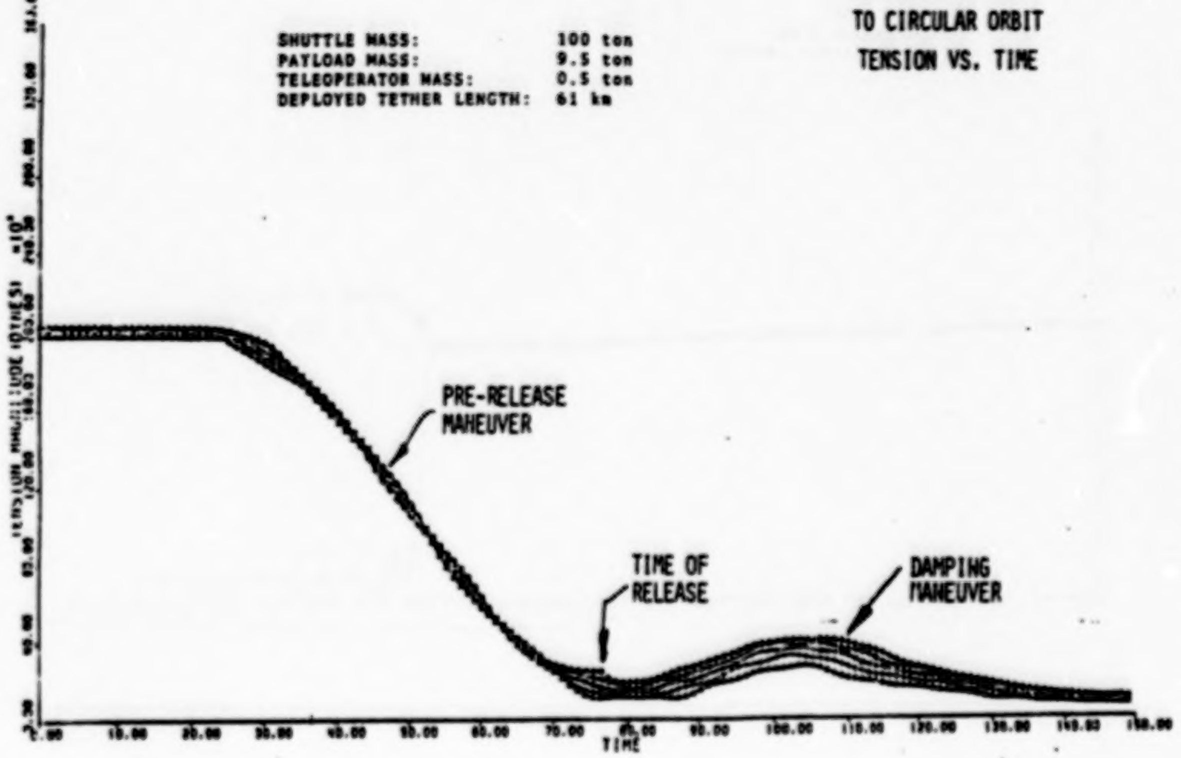
PAYLOAD RELEASE
TO CIRCULAR ORBIT

RADIAL VS. IN-PLANE BEHAVIOR
AT 10 SECOND INTERVALS
SCALE EXPANSION: 12X

15 JUNE 1983

Shuttle Mass: 100 ton
Payload Mass: 9.5 ton
Teleoperator Mass: 0.5 ton
Deployed Tether Length: 61 km

PAYLOAD RELEASE
TO CIRCULAR ORBIT
TENSION VS. TIME



15 JUNE 1983

TETHER DYNAMICS RESEARCH
PROBLEM AREAS

1. TETHER SAFETY AND ABORT MODES
    - REEL JAM AND WIRE BREAK CONDITIONS
    - CONTROL FAILURES
2. CONTROL LAW DEVELOPMENT AND VERIFICATION
3. IN-ORBIT PREDICTIVE MODELLING
4. SUBSATELLITE DYNAMICS
    - RIGID BODY DYNAMICS
    - REACTION TO ATTITUDE CONTROL

SUGGESTED SKYHOOK DEVELOPMENT

1. IMPROVE TETHER MOTION RESOLUTION
    - INCREASE MASS POINTS TO AT LEAST 100
    - VARIABLE DISTRIBUTION WITH CURVATURE AND/OR TENSION

2. INCREASE COMPUTATIONAL SPEED
    - ABORT EVENT ANALYSIS
    - IN-ORBIT CAPABILITY

3. UPGRADE COMPUTATIONAL CAPABILITY

N85-20371

III. TETHER MANUFACTURING CONCEPT

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PULTRUSION PROCESS FOR FABRICATION OF TETHERS (PRELIMINARY CONCEPTS)

FOR

APPLICATION OF TETHERS IN SPACE WORKSHOP
(TECHNOLOGY AND TEST)

WILLIAMSBURG, VA, JUNE 15-17, 1983

BY

IAN. O MACCONOCHIE (SSD) AND HAYWOOD L. WILSON (FD)

LARC 6-15-83

ABSTRACT

Three composite materials have been manufactured by the pultrusion process, coiled on 24" diameter spools for a period of two months, uncoiled and evaluated for memory recall. These materials were pultruded to lengths of approximately 150 feet and cross section profiles were maintained at 0.143 inch in thickness by 0.566 inch in width. Mechanical properties were conducted and results compared. The reinforcement material volume percent of each was identical. Of the three systems, the Kevlar reinforced composite had the highest specific strength, the lowest flexural modulus, and the lowest memory recall.

Further evaluations of materials and fabrication technology of pultrusion should be conducted to address some problem areas encountered in this preliminary concept. The following areas are suggested for further study:

*Evaluate and correct cause of Kevlar reinforced polyester composite low memory recall (wetting problem).

*Evaluate several resin systems and formulations to include epoxies, polyesters, and vinyl esters, with and without ultraviolet stabilizers.

*Compare properties of composites made with above resin systems reinforced with fiberglass and Kevlar, of round and rectangular profiles.

*Evaluate a tapered tether with internal electrical cable concept.

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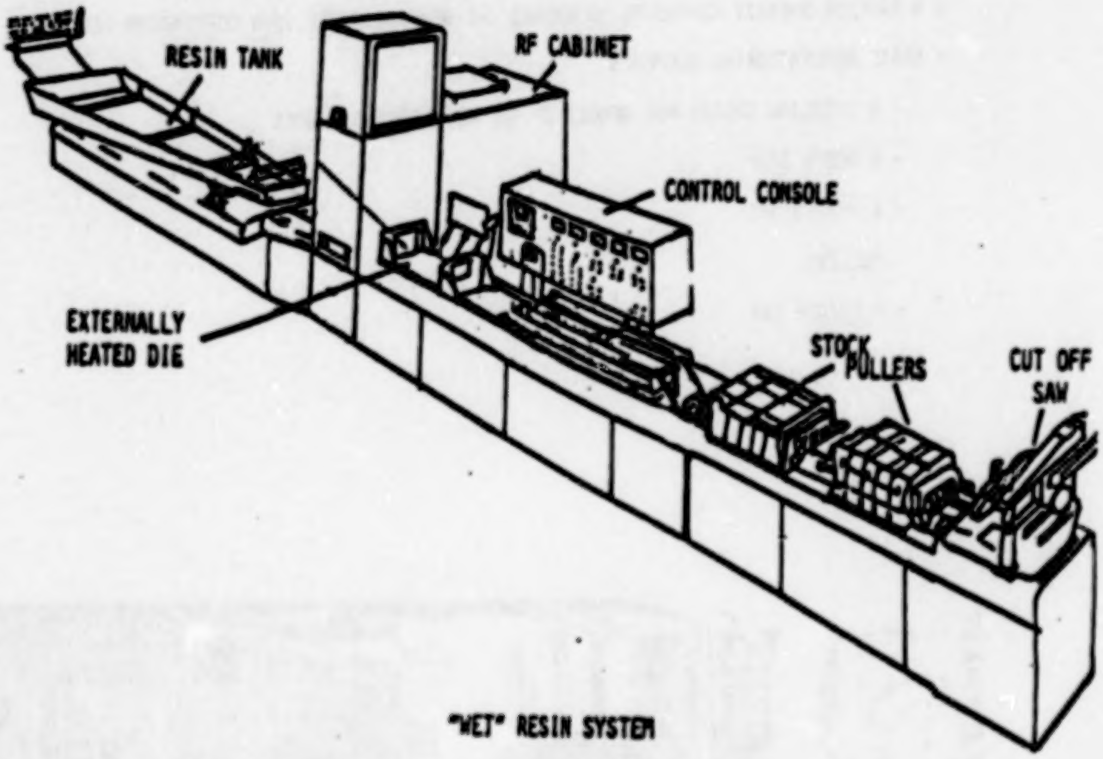
THE PULTRUSION PROCESS

- A PROCESS WHEREBY COMPOSITE MATERIALS CAN BE FABRICATED INTO CONTINUOUS LENGTHS
- BASIC MANUFACTURING ELEMENTS
    - A CREELING SYSTEM FOR SPOOLS OF THE REINFORCING FIBERS
    - A RESIN BATH
    - A HEATED DIE
    - PULLERS
    - A CUTOFF SAW

LARC PULTRUSION MACHINE


RESIN TANK
RF CABINET
CONTROL CONSOLE
EXTERNALLY HEATED DIE
STOCK
PULLERS
CUT OFF SAW

"WET" RESIN SYSTEM

WHY PULTRUSION FOR TETHERS?

- PULTRUDED MATERIAL HAS A HIGH SPECIFIC STRENGTH
- TETHERS CAN BE TAPERED
- TETHERS CAN BE MANUFACTURED IN CONTINUOUS LENGTHS

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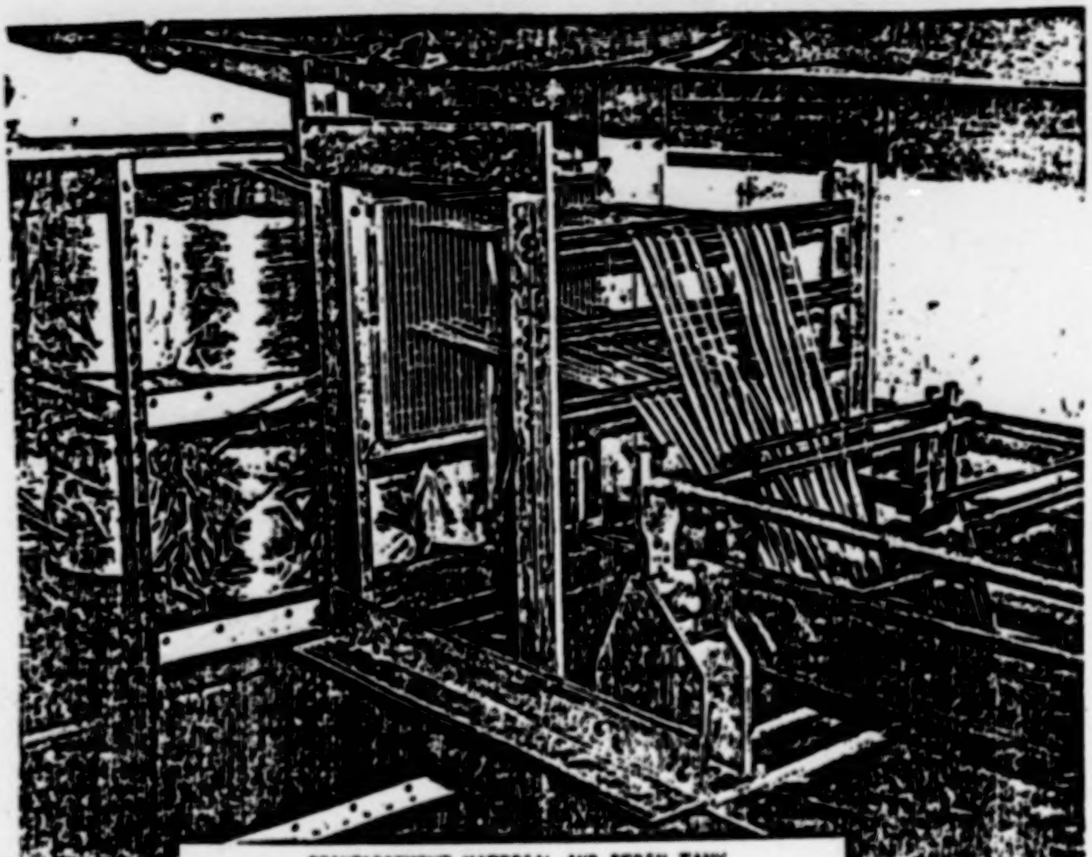
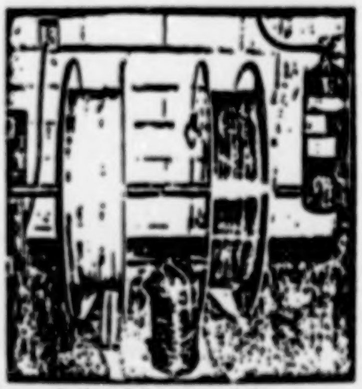


REINFORCEMENT MATERIAL AND RESIN TANK

Cure Die and Pultruded Composite Exiting.



Coils of Test Materials

Top View of Uncoiled Specimens

Side View of Uncoiled Specimens

PULTRUDED TETHER
SPOOL STORAGE TEST
2.5 MONTHS ON 24 INCH DIA. SPOOL

TEST SPECIMEN			STORAGE			MEMORY
	THICK	WIDTH	STRESS	RADII, INCHES		RECALL
MATERIAL	IN.	IN.	PSI	STORED	RELEASED	%
KEVLAR/POLY	0.143	0.559	11,560	12	110	89.0
GLASS/POLY	0.143	0.566	23,849	12	672	98.2
GLASS/VINYL	0.142	0.562	24,161	12	750	98.4

PULTRUDED MATERIALS
PROPERTY DATA

TEST SPECIMENS	FIBER WT. %	DENSITY LBS/IN^3	TENSILE STRENGTH KSI	SPECIFIC STRENGTH X10^6	FLEXURAL MODULUS X10^6 PSI
KEVLAR/POLYESTER	48	0.046	107	2.3	1.94
GLASS/POLYESTER	63.5	0.062	75	1.2	4.00
GLASS/VINYL ESTER	63.0	0.063	69	1.1	4.08

PROPOSED FURTHER EVALUATIONS
OF
MATERIALS AND TECHNOLOGY
FOR
TETHER MANUFACTURING
BY
THE PULTRUSION PROCESS

- EVALUATE AND CORRECT CAUSE OF KEVLAR REINFORCED POLYESTER COMPOSITE LOW MEMORY RECALL (WETTING PROBLEM).
- EVALUATE SEVERAL RESIN SYSTEMS AND FORMULATIONS TO INCLUDE EPOXIES, POLYESTERS, & VINYL ESTERS, WITH AND WITHOUT ULTRAVIOLET STABILIZERS.
- COMPARE PROPERTIES OF COMPOSITES MADE WITH ABOVE RESIN SYSTEMS REINFORCED WITH FIBERGLASS AND KEVLAR, OF ROUND AND RECTANGULAR PROFILES.
- EVALUATE A TAPERED TETHER WITH INTERNAL ELECTRICAL CABLE CONCEPT.

SUMMARY REMARKS

- SOME PRELIMINARY EXPERIMENTS IN THE MANUFACTURE AND STORAGE OF PULTRUDED TETHERS HAVE BEEN MADE
- KEVLAR/POLYESTER STORES AT A LOWER STRESS THAN GLASS/POLYESTER BUT SHOWS A HIGHER PERMANENT SET

IV. APPLICATIONS

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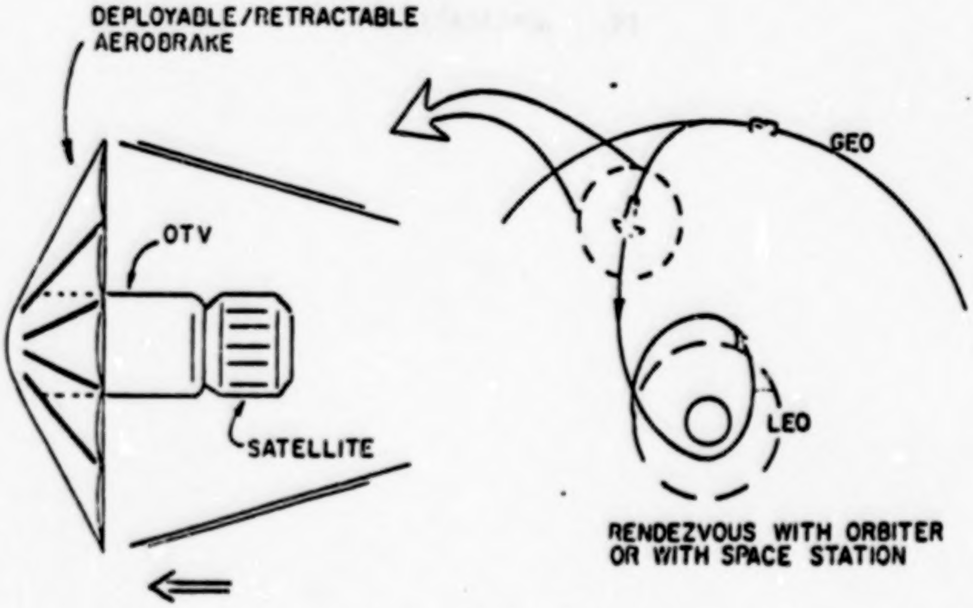
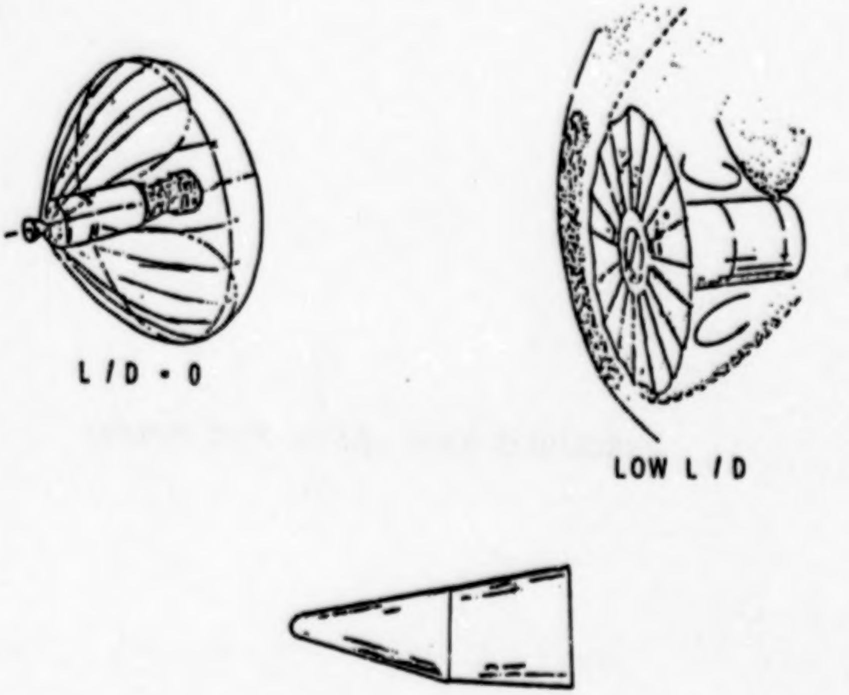
APPLICATION NO. 1 - TETHER AS A WIND TUNNEL RAREFIELD FLOW RESEARCH

KENNETH SUTTON

AERO-ASSIST GEO TO LEO


DEPLOYABLE/RETRACTABLE AEROBRAKE
OTV
SATELLITE
GEO
LEO
RENDEZVOUS WITH ORBITER OR WITH SPACE STATION

AOTV CONCEPTS



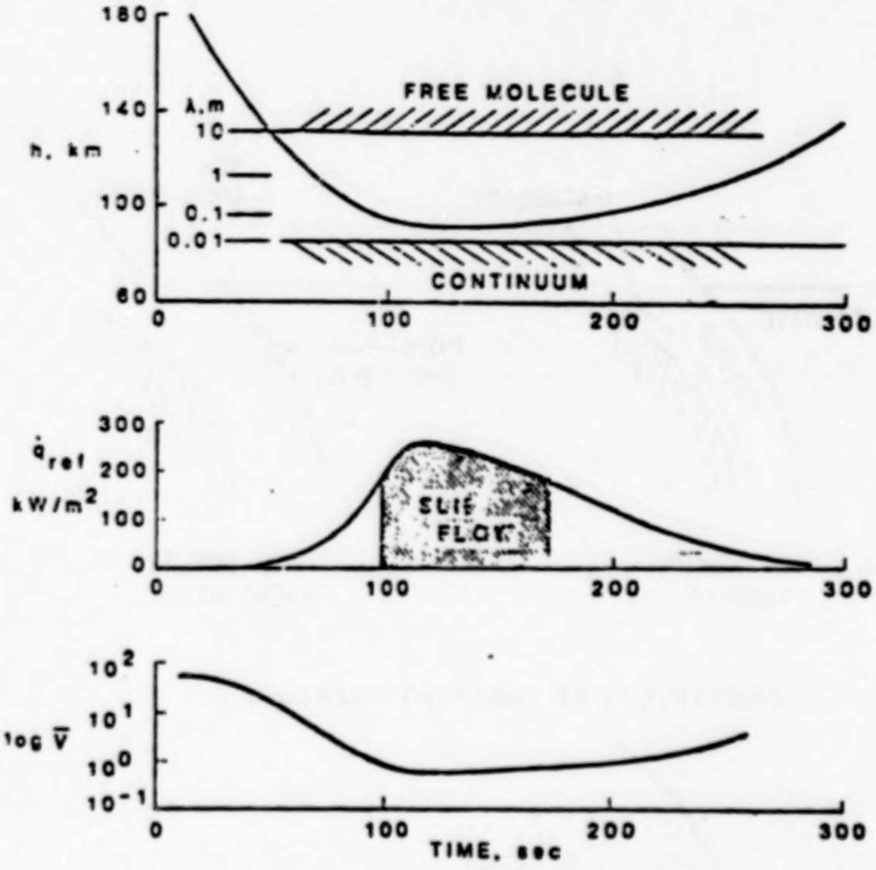
L/D = 0

LOW L/D

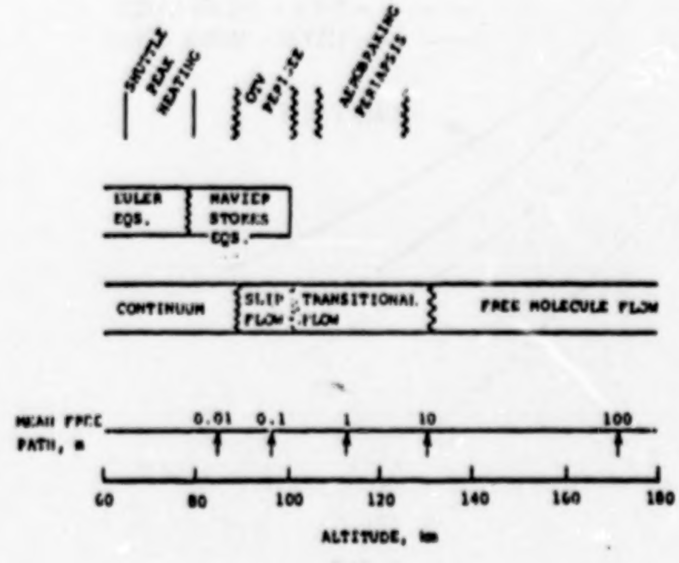
L/D = .75 - 1.5

OTV TRAJECTORY

$L/D = 0.5,\ M/C_D A = 20,\ kg/m^2$

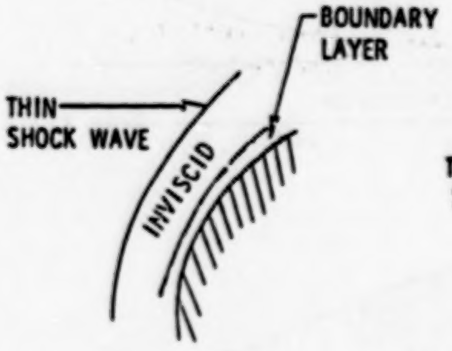


HIGH ALTITUDE FLOW REGIMES

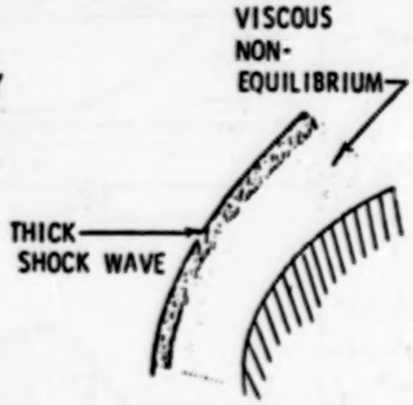


SHUTTLE PEAK HEATING
OTV PERIGEE
AEROBRAKING PERIAPSIS
EULER EQS.
NAVIER STOKES EQS.
CONTINUUM
SLIP FLOW
TRANSITIONAL FLOW
FREE MOLECULE FLOW
MEAN FREE PATH, m
0.01
0.1
1
10
100
60
80
100
120
140
160
180
ALTITUDE, km

LOW DENSITY EFFECTS ON SHOCK LAYER

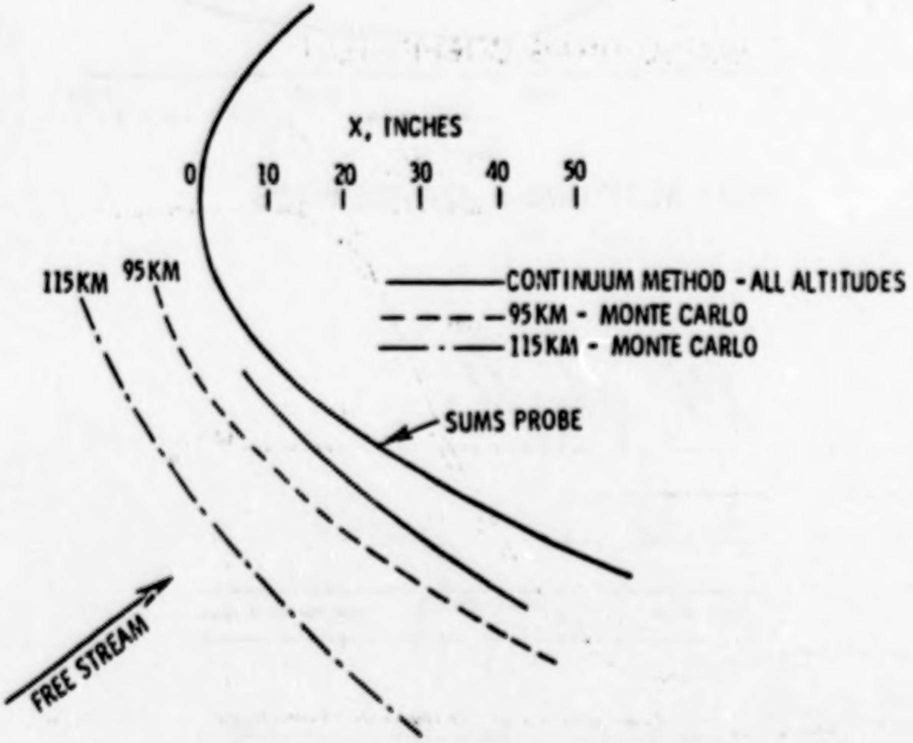

BOUNDARY LAYER
THIN SHOCK WAVE
INVISCID

HIGH DENSITY
(ENTRY)


VISCOUS NON-EQUILIBRIUM
THICK SHOCK WAVE

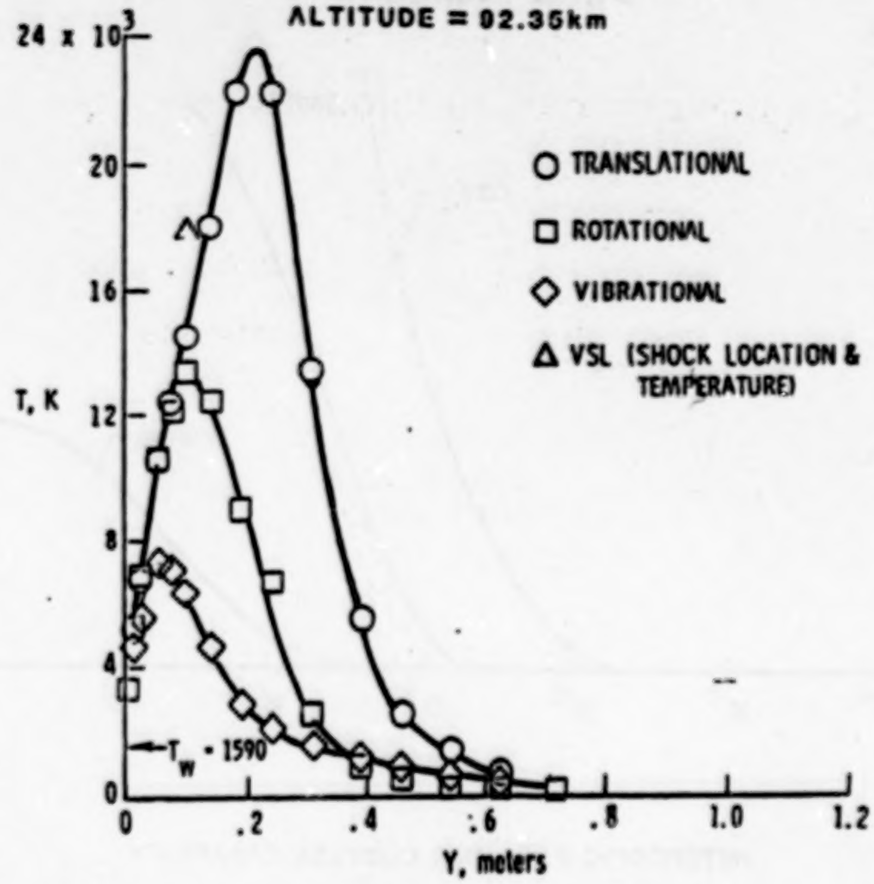
LOW DENSITY
(AERO ASSIST)

COMPARISON OF SHOCK ON PARABOLOID

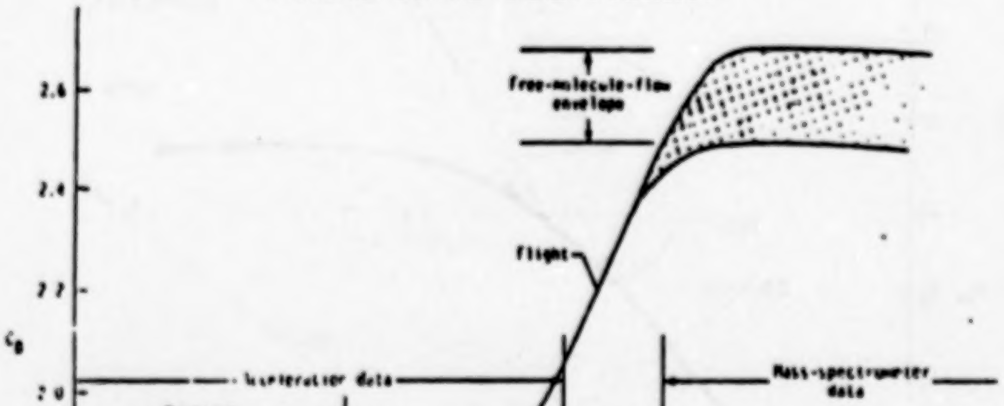

X, INCHES
0
10
20
30
40
50
115KM
95KM
CONTINUUM METHOD - ALL ALTITUDES
95KM - MONTE CARLO
115KM - MONTE CARLO
SUMS PROBE
FREE STREAM

NON-EQUILIBRIUM EFFECTS

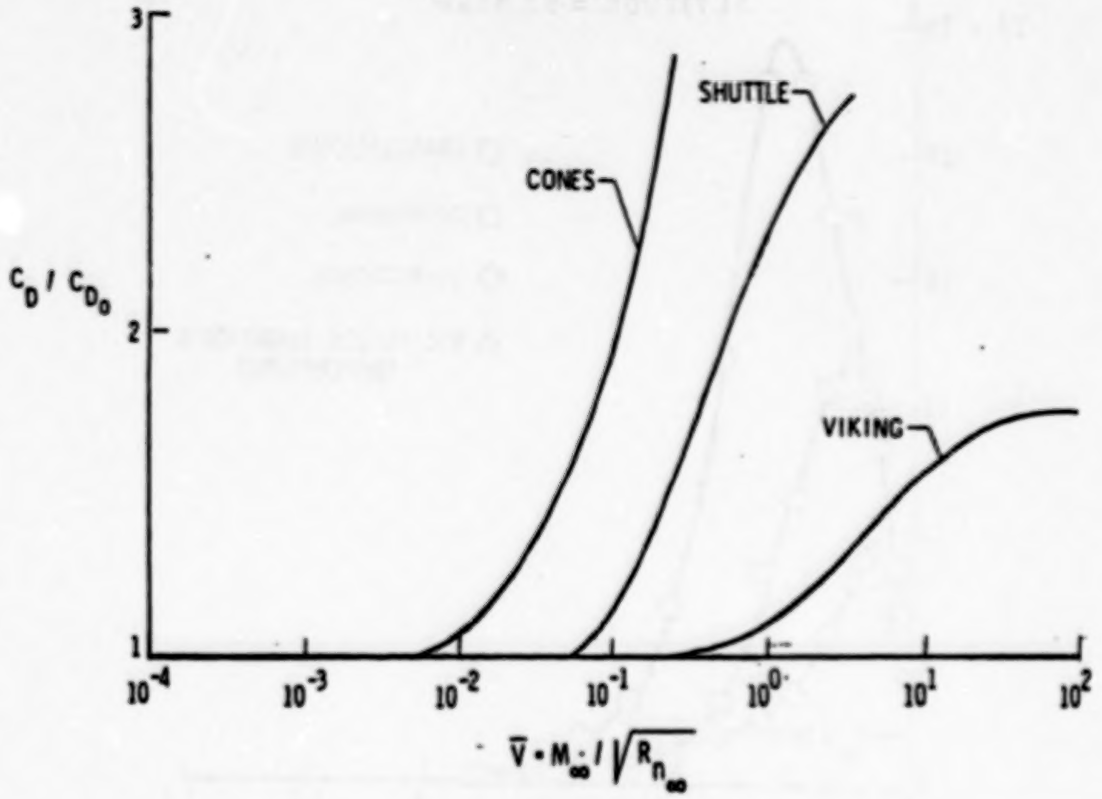
ALTITUDE = 92.35km



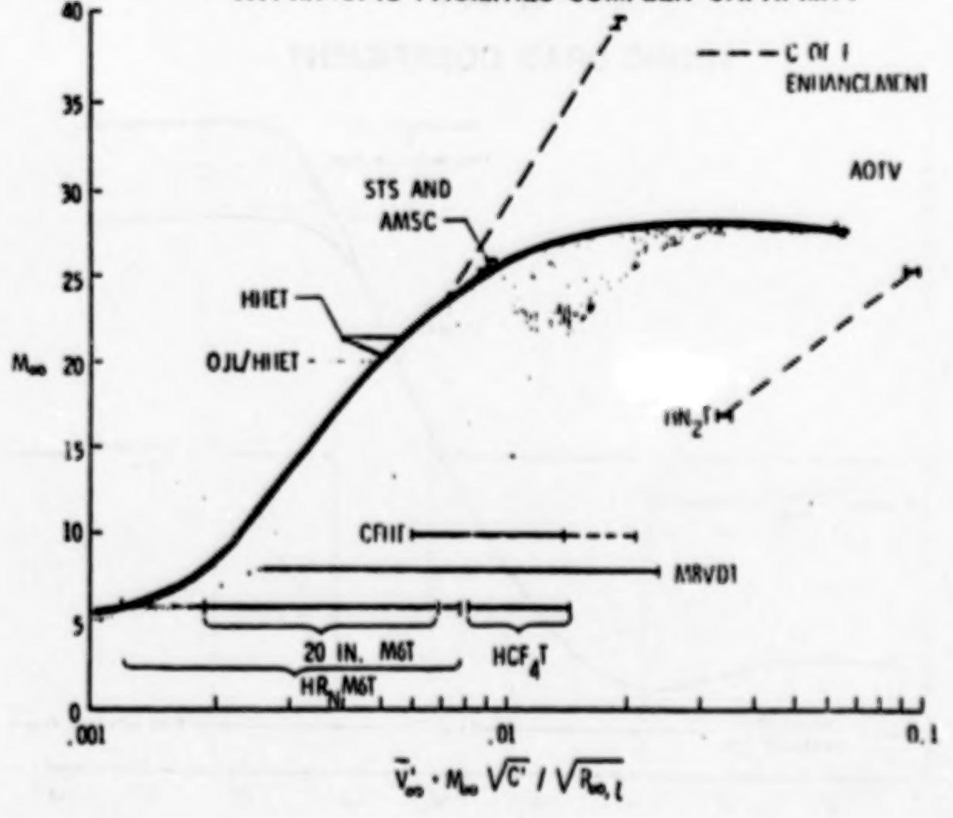
VIKING DRAG COEFFICIENT

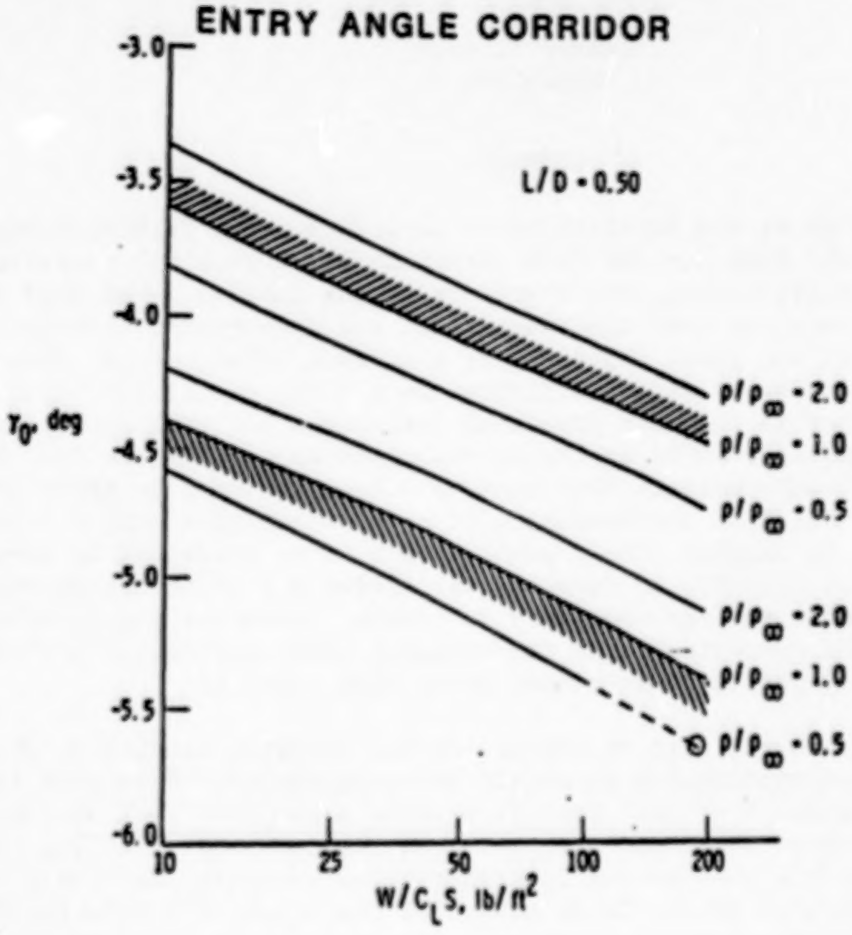


DRAG INCREASE



HYPERSONIC FACILITIES COMPLEX CAPABILITY





ENTRY ANGLE CORRIDOR

TETHER AS A WIND TUNNEL

RAREFIED FLOW RESEARCH

ALTITUDE: APPROXIMATELY 90-110 KM

RESEARCH NEEDS:
- AERODYNAMICS
- HEAT TRANSFER
- FLOW-FIELD CHARACTERISTICS
- COMPUTATIONAL TECHNIQUES VALIDATION
- CONFIGURATION TESTING

UPPER ATMOSPHERE DENSITY

N85-20372

INSTRUMENTATION FOR APPLICATION NO. 1

MASS SPECTROMETRIC ANALYSIS OF THE BOUNDARY LAYER ASSOCIATED WITH THE TETHERED SATELLITE

George M. Wood
NASA-LaRC

SUMMARY

Knowledge about the boundary layer associated with high enthalpy flow fields has mostly been derived from measurements of physical properties. To further this understanding, the chemistry of the gaseous layer must be studied as well. This requires that instrumentation and measurement methods be developed that can analyze the gases while having a minimal effect on the flow field and composition. Because of its sensitivity and ability to identify species, the mass spectrometer is the most promising instrument for this application, although other spectroscopic methods are being evaluated as well. There are, however, several non-trivial problems that must be solved in order to apply the mass spectrometer, including the obtaining of a representative sample from near the model surface. At Langley, these problems are being addressed in a research program (Wood et al,1983) to develop qualitative and quantitative measurement methods to examine the gas chemistry in several large hot-gas blowdown facilities, and to study the aerodynamics of the boundary layer associated with models in these facilities and in instrumented hypersonic vehicles.

These methods can also be applied to the tethered satellite, which will provide a unique opportunity to obtain aerothermodynamic data that is unaltered by effects from the test facility. It must be emphasised that in these and other measurements associated with tests on the tethered satellite, it cannot be assumed that the methods and instrumentation necessary to obtain high quality data already exist. It is essential therefore that once tests are defined that the measurement requirements be critically examined and such development as necessary be initiated.

INTRODUCTION

At the close of the Thursday session, members of the Technology and Test Panel were asked to consider testing of not only those items that we had identified ourselves, but also those identified by the other panels in their deliberations. I suggest that "test" is not yet the correct term, as it implies that adequate instrumentation and measurement methods exist to perform these tests and to obtain data over the required measurement range with sufficient reliability, response, precision, and accuracy, Clearly, this availability has not been established for the tethered satellite. Once the tests have been defined, one must first look to the measurements and their methodology before proceeding.

Tests concerning the tethered satellite will fall into two catagories: those on the satellite and its tether; and, those on the environment surrounding it. The first catagory has to do with the deployment and well-being of the of the satellite, and will include such parameters as tension, temperature, and charge distribution along the tether; internal and surface temperatures and pressures, velocity, drag, and exact location of the satellite. The second are those concerned with the use of the satellite as a test platform for aerothermodynamic and atmospheric investigations from which contamination and enclosure effect, such as those imposed by the tunnel walls, have been minimized. In order to use the satellite for these aerothermodynamic studies, it is imperative that the atmosphere in which it is moving be both physically and chemically characterized.

Historically, thermodynamic flow properties of gases in the boundary layer or the flow field have been deduced from pressures and temperatures measured on a model. The understanding of these properties has reached the point where further progress requires more complete characterization of the layer including determination of the gas composition and chemistry. This in turn requires species identification and reactant-product determinations, therefore, most attempts to measure boundary layer chemistry involve a mass spectrometer and its associated gas sampling system. Other spectroscopic methods have been used, but are limited due to configurational, noise, wavelength, or scattering problems for this application (Miles et al, 1983). Mass spectrometric techniques for gas analysis are capable of simultaneous real-time measurement of the identity and concentration of a chemical species. However, if the gas composition to be measured is in a hypersonic high enthalpy stream flowing around a vehicle or model surface, then special techniques and systems are necessary to meet the sampling criteria for the various flow regimes involved. Obtaining the representative sample for mass spectrometric analysis that is unaltered, or is altered in a quantitatively determinable manner is therefore not a trivial problem. The electronic and vacuum operating requirements of the mass spectrometer, along with its configuration also complicate its application in these studies.

A major problem for hypersonic test vehicles is understanding the aerothermodynamics controlling vehicle performance and consequently predicting aerothermal behavior that can reduce the conservatism in designing active or passive thermal protection systems. The hypersonic vehicles affected by this unknown behavior include aero-assisted orbit transfer vehicles (Walberg, 1982), ballistic entry vehicles for possible space station rescue, hypersonic cruise vehicles, and improved space Shuttle orbitors (Hays, 1981). The difficulty in designing thermal protection systems for these vehicles is in part due to the limited knowledge of the behavior and mechanisms of dissociated gas species in the presence of catalytic materials and the lack of suitable test facilities and techniques for measuring the gas behavior (Eide, et al, 1981). The need to sample boundary layers near the surface is exemplified by the data in figure 1, (Shinn et al, 1982) which shows the calculated mass fractions of atomic oxygen and nitrogen at a high altitude point along the second Space Shuttle entry trajectory. For either a noncatalytic wall or an equlibrium catalytic wall which promotes instantaneous reactions the mass fraction of the O and N species approach one another quite rapidly along a ray away from the wall surface. Should the sampling penetration volume extend out to a 0.1 nose radius there would be averaging and perturbation effects resulting in quite limited information gained about the surface recombination rate associated with a particular vehicle wall material. Because of these surface related effects, the gas sampling should be at least quasi-non-intrusive with controlled penetration of the boundary layer, mass scanning and data acquisition rates should be fast enough to monitor rapidly fluctuating conditions, and mass resolution should be sufficient to identify gaseous species through measurement of exact mass alone.

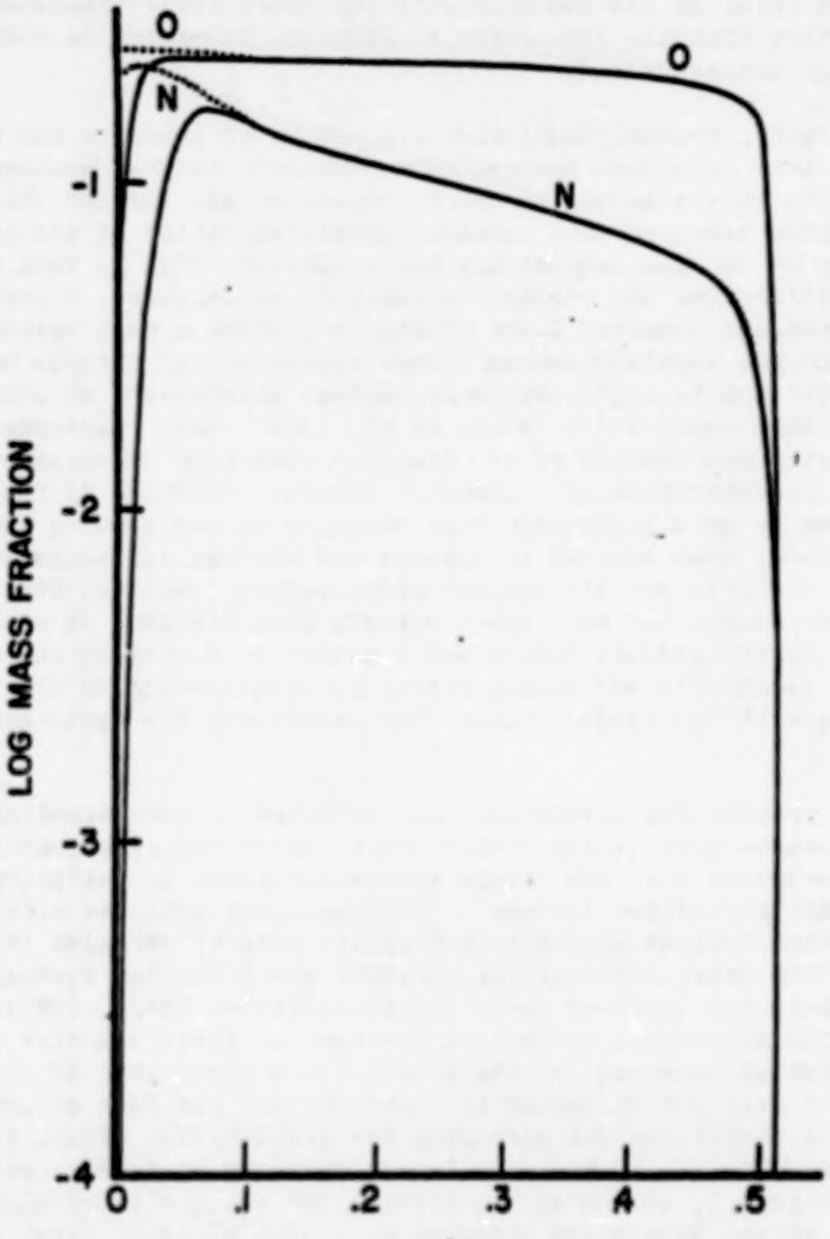


Figure 1.- Species mass fraction as a function of distance from the surface in terms of fractional nose radius for nonequilibrium flow over equilibrium catalytic (solid line) and noncatalytic wall (dotted line), adapted from Shinn et al, (1982).

PROGRAM DESCRIPTION

The three major limiting factors which must be addressed for successfully implementing a mass spectrometer in aerothermodynamic investigations on models at re-entry stream velocities, are: gas sampling effects; instrument limitations; and problems with data acquisition. The research at LaRC is a concentrated effort to quantitatively identify and correct for instrument and sampling system effects, and to develop a miniaturized high performance mass spectrometer for on-model real-time analysis of the boundary layer and its associated atmosphere, both in ground based facilities and on-board a re-entry hypersonic test vehicle. This same instrument will be applicable to measurements with a tethered satellite.

The essential requirements for any sample are that its spatial and temporal boundaries be known and that its physical and chemical states either not be changed by the sampling process or be changed only in a predictable and measurable way. High enthalpy conditions therefore present specific and highly challenging sampling problems. Additionally, ground based high enthalpy test facilities are limited in run time and therefore require measurements approaching real-time if fast transient events are to be detected.

Previous applications of mass spectrometry in investigating hypersonic flow and combustion research have used a probe facing directly into the flow as the inlet (Trinks, 1973; Crane and Stalker, 1977; Offerman and Tatarczy, 1973; Melfi et al, 1974). Such probing may perturb the normal flow about a body, change pressure distributions, and also may change the atomic and molecular concentrations of the gaseous specie, many of which are dissociated and/or quite reactive, across the shock at the inlet thus complicating the interpretation of the resulting data. It has been proposed (Miles et al, 1983) that one means of eliminating the problem of measuring such unstable or dissociated species is the seeding of the gas mixture with another gas which would react with these species in a predictable manner to form stable products. This approach has been applied in a study of combustion products in which the dissociated species were reacted with deuterium (Fristrom and McLean, 1982). Such labeling would not resolve the flow perturbation problem since any alteration of flow about the body cannot be tolerated if the boundary layer is being measured. An additional problem occurs if catalytic or absorptive tubing materials are used to transport the sample from the sampling point to the spectrometer source. Any temperature variation in the sampling systems may also have its effect on the data.

In any investigation of aerothermodynamic characteristics, the atmospheric data obtained from these forward (or aft) facing inlets are extremely important. On the other hand, it is also important that data be obtained near the surface from a minimally disturbed flow field. Our approach to obtain representative samples from within the boundary layer will involve the use of sampling devices consisting of either a pitot tube, a single flush pumped orifice, or of multiple flush orifices. These devices must have flow characteristics through the opening that limit the depth of penetration into the boundary layer since flow field perturbations must be minimized in order to sample close to the surface. A single flush orifice, figure 2, is being computer modeled and a theoretical analysis will be performed to estimate sampling penetration depths into the boundary layer under various expected conditions as a function of temperature, pressure, orifice size, pumping speed, and boundary layer composition and flow velocity. By controlling pumping speed at the inlet, sample distance from the wall can be varied within limits due to the pressure depression resulting from the pumping action.

These computer model calculations will also be used to establish design parameters for the development of a multiple orifice nonintrusive effusive sampling device which will serve as a direct inlet into an in-model mass spectrometer. The effusive inlet conceptualized in figure 3a, is comprised of an array of parallel micron size capillaries, with an array density of approximately $10^5/cm^2$. Atoms or molecules scattered into the capillaries will either pass directly through, or will be reflected from the capillary wall into the ion source or back into the gas stream. Because the effective pumping speed at the capillary inlet will approach zero, pressure deformation of the flow field will be minimized and the sampled species will be obtained from within a few mean free paths of the surface. Dissociated species reacting with the capillary will be identified by coating the wall with an isotopically labeled substance or by labeling the wall itself. The resulting labeled product from the reaction on the surface will differentiate between dissociated and nondissociated species entering the inlet.

Characteristic transport rates through small diameter tubes to the mass spectrometer are being determined in the laboratory as a function of tube length, pressure differential and gas species. These measurements are being carried out with both pure gases and known mixtures to determine diffusive or gas-wall fractionating characteristics if they exist. Candidate materials for sampling device fabrication are being evaluated for possible chemical and catalytic reactivity with the gases of interest under designated sampling conditions. The devices to be characterized in the laboratory studies include flush surface orifices, pitot tubes, and the yet to be developed non-intrusive multiple orifice surface sampling effusive inlet device. The laboratory test system will consist of the sampling device, transfer line, and mass spectrometer. The flow test data will be quantitatively evaluated for both static conditions and for relatively low velocity gas streams as a function of temperature and inlet pressure.

Attempts will be made to determine the sample constraints for each measurement system selected for tunnel experiments. Preliminary theoretical calculations indicate that the penetration depth of sampling into laminar boundary layers by flush orifices can be calculated from aerodynamic parameters, orifice diameter, and pressure drops across the sampling tube (Brown, 1983). Sampling penetration and/or perturbation depths will be evaluated experimentally if possible under measured flow velocities in the laboratory and in actual tunnel runs using shadowgraphs to verify the theoretical model calculations.

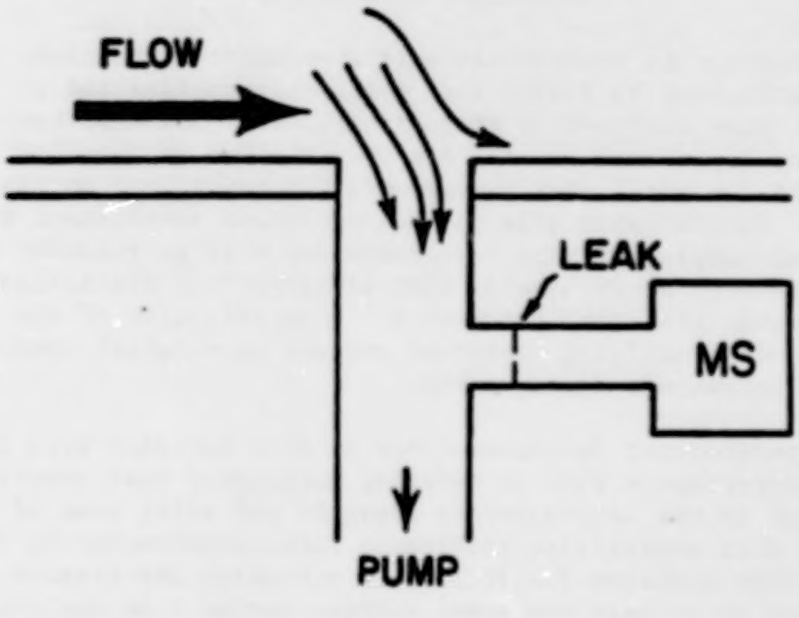


Figure 2.- Schematic representation of a mass spectrometric pumped flush orifice sampling system for measuring composition of gases flowing over a surface, where flow is parallel to the surface and the sample is pumped past the inlet leak to the mass spectrometer.

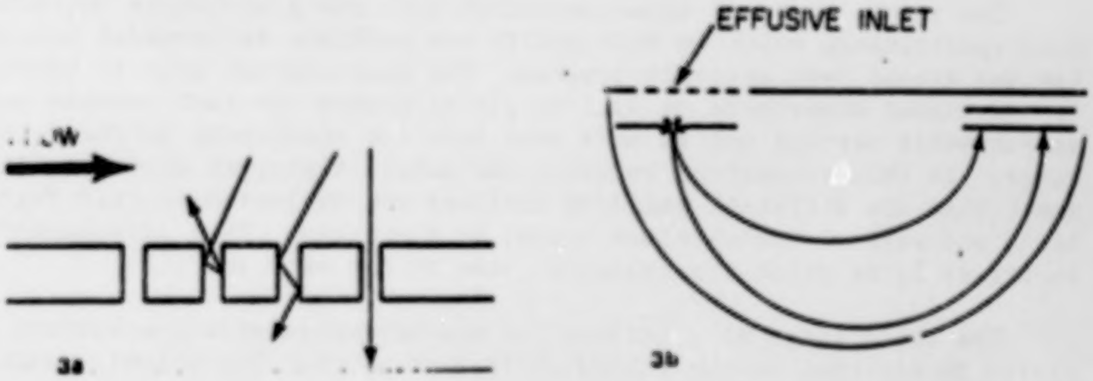


Figure 3.- Schematic representation of the proposed nonintrusive mass spectrometric measurement system featuring: (a) an effusive inlet of many capillary holes in a thin plate mounted flush with the surface and connected directly to (b) an in-model, miniaturized mass spectrometer.

INSTRUMENT DEVELOPMENT

Mass spectrometry is perhaps the only instrumental technique with a response time sufficient to follow fast chemical reactions and at the same time afford real time analyses of complex mixtures. Its application in high enthalpy boundary layer measurements has been limited by sampling of the free stream gas and by the small size requirement for installing an instrument inside a model. Coupled with size is the resolution requirement usually needed to unravel complex spectra. Furthermore, a large quantity of data must be taken during a very short time as high enthalpy test facilities may operate for periods somewhat less than one minute. Interpretation of the data must include a means of identifying transient changes in chemical composition and sampling volume parameters during a run.

Our mass spectrometer development for on-line analyses will proceed in three stages. Experiments with an existing quadrupole mass spectrometer are being carried out in the laboratory to identify and solve some of the measurement and data acquisition problems. This spectrometer is also being used in a LaRC high enthalpy facility as an off-model measurement device. Samples are taken at or near the model surface during film cooling and and other aerothermodynamic experiments, and transported through a long tube for subsequent analyses. Additional samples will be obtained from intrusive pitot probes mounted on the sting or model and by penetrating the tunnel wall at various locations. This data will be used to study the sampling problems under these conditions and to examine the tunnel gas chemistry. While this first development stage will be limited by the data acquisition times and sample transport lag time problems, some quantitative data will be obtained and additional measurement and instrumental effect problems will be clarified.

The second stage of experimentation will use a miniature magnetic sector mass spectrometer which we will modify and dedicate to in-model measurements for the ground test research program. The spectrometer will be close-coupled to the tunnel atmosphere or will be placed within the test vehicle and measurements carried out as were done with the quadrupole in the first stage. In this situation, however, the sample transport distance will be very short when the different sampling orifices are evaluated so that transport lag times and surface interactions should be minimized. This arrangement is shown in figure 2, in which the transport tube is now very short.

The third stage will utilize the non-intrusive effusive surface inlet system in addition to the pumped orifice or pitot. The effusive inlet will allow the gaseous sample to pass directly into the ion source of a miniaturized mass spectrometer which will be mounted in the model or re-entry vehicle. This spectrometer, as outlined in figure 3b, will be a 180° magnetic deflection instrument having a radius of approximately 7.6 cm (3.0 in) and an outward radial magnetic field inhomogeneity of +0.5 to increase the mass dispersion by a factor of two, hence improving the resolution/size relationship. The projected resolution will exceed 1 part in 2500, or, that required to resolve nitrogen and carbon monoxide at the nominal mass of 28. Ions will be detected and measured with a continuous multichannel plate (Wiza, 1979) electron multiplier array directly interfaced to a solid state Large Scale Integration or charge coupled Device, (White, 1982) figure 4, to image and measure the intensity of each mass-resolved ion beam over the range of 2 to 100 amu. Essentially simultaneous measurement of the beam by interrogating

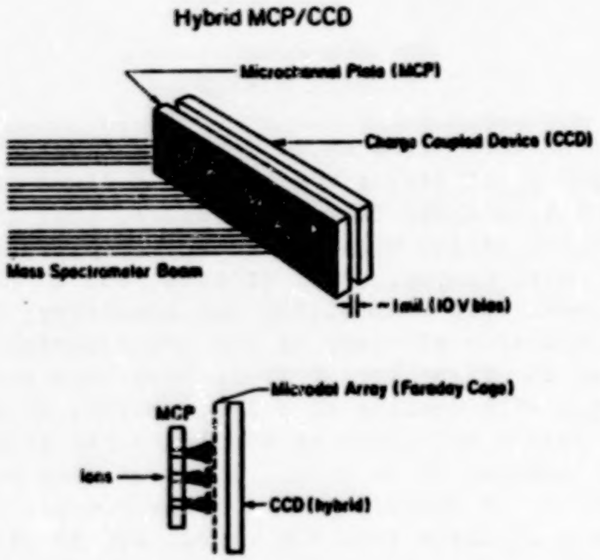


Figure 4.- Schematic representation of the proposed fast ion detector which will be capable of simultaneous measurement of all masses between 2 and 100 amu (White, 1982).

the device at a nanosecond rate will preclude the necessity for magnetically or electrostatically scanning the mass spectrometer, thus simplifying electronic requirements and increasing stability.

Adequate technology exists for fabricating the inhomogeneous field magnet, the problem primarily being one of miniaturization and machining to close tolerances. The effusive inlet, and more so the detector, are presently beyond the state-of-the-art, and will require significant research and development. This approach should eliminate sample transport delay problems and provide a full range mass measurement. This technique will provide a statistically valid mass data base array of information in real time which can be enhanced as necessary to provide improved resolution utilizing the mathematical deconvolution techniques which were reported earlier (Wood et al, 1981). Interrogation of such a real-time data base matrix will provide the information necessary to measure changes in the total pressure at the effusive inlet, along with species identification and concentration changes in the sample volume to include transient species, as well as the identification of spurious signals as transients. This new technology will thus make it possible to monitor compositional changes in a medium without perturbing the medium. Furthermore, the sample will be representative under constant or variable pressure conditions, and the ability to monitor both total and partial pressures will eliminate the need for sampling volume and pressure constraints otherwise required for gas analysis using conventional mass spectrometric or other currently available techniques.

PROGRAM STATUS

The initial part of this research is directed towards: optimizing sampling through shaped pitot probes and through a flush orifice in a surface parallel to the flow with minimal flow disturbance, that is, quasi-non-intrusively; to the quantitative measurement of mixing ratios in seeded or isotopically labeled multi-component gas streams; and to accurate characterization of tunnel gas composition and chemistry, including identification and correction of sampling and instrumental effects. Some experiments concerning the first two of these have been performed during studies of nitrogen-gas film-cooling of a large model, in which the nitrogen used for cooling was seeded with neon as the inert gas tracer. These experiments were not intended to be quantitative at this point, but were to determine the feasibility of operating in a large hot-gas facility with the instrument located some distance from the model, and to identify problem areas so that satisfactory measurement methods could be devised.

The research was performed in the Langley Research Center's 8-foot High Temperature Tunnel. This facility, which is a large Mach 6.8 blow-down tunnel, uses methane-air combustion at total combustion pressures of 600-4000 psi to achieve the high energy levels for flight simulation over an altitude range of 80 to 130 thousand feet. The test medium consists principally of N_2, O_2, CO_2, and H_2O, with the mass fraction varying with the amount of fuel reacted, and hence with the stagnation temperature (Howell and Hunt, 1972). The wind tunnel as shown schematically in figure 5, consists of a combustor, hypersonic nozzle, test section, supersonic diffuser, air ejector, mixing tube, and a subsonic diffuser.

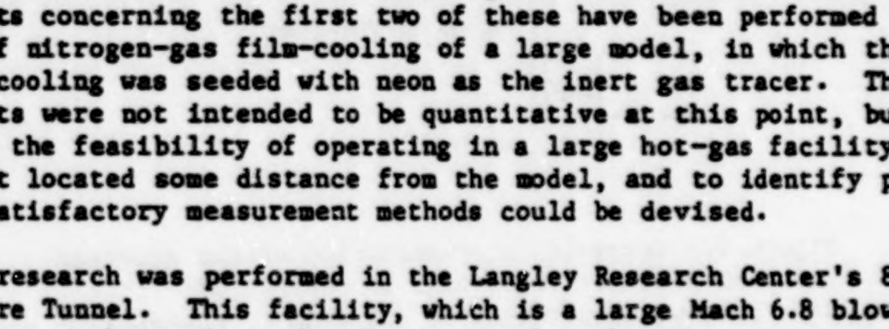


Figure 5.- Schematic drawing of the 8 foot High Temperature Tunnel at Langley Research Center.

The test chamber is 8 feet in diameter and 14 feet long with a usable flow core of 5 feet operating as a free jet. It is enclosed in a 26-foot-diameter sphere over a 16-foot-diameter pod containing a hydraulic model injection carriage. Once the desired flow conditions are established, the model is inserted into the test stream in about 1.0 seconds to approximate a step heat-input to the model.

The experiments were carried out at Mach 6.8, with experiment run times typically being 10–20 seconds long, with a few lasting as long as 40 seconds. A thermochemical equilibrium computer program (ACE) (Kendall, 1968) was used to calculate gas composition, thermodynamic transport, and flow properties. Test conditions were as follows: combustor total pressure, 17.2 MPa (2500 psi); free stream pressure 2.12 kPa (0.31 psi); dynamic stream pressure 68.9 kPa (10.1 psi); total temperature 1889°K (3400°R); total enthalpy 2370 kJ/kg (1020 Btu/lb); and mole fractions of .050 for O_2, .724 for N_2, .072 for CO_2, .145 for H_2O, and .009 for Ar.

The model, figure 6, is a 162.6 cm (64 in) long conical frustrum, with a 91.4 cm (36 in) diameter base and a 12.5° half angle. The ogive nose has a 4.1 cm (1.6 in) diameter forward facing coolant ejection port. Gases were first sampled from the forward retractable probes which are deployed during the test after insertion of the model. Similar retractable probes will be used on subsequent tests to characterize the flow field near the model surface. Subsequently, samples were obtained through the flush mounted eliptical pitot and orifice shown in detail in figure 7. The elliptical pitot is a 3.18 mm (.125 in) tube, flattened and welded to the sample plate. A chromel/alumel thermocouple mounted on the backside of the plate measured temperature and heating rate. These ports were invididually connected to the mass spectrometer inlet system through 18.3 m (60 ft) 1.65 in) i.d. tubing terminating in a vacuum pump. Gas flows were simultaneously established in both tubes. Switching from one port to the other during the run was accomplished remotely at the mass spectrometer to minimize the delay which would have resulted from re-establishing flows if the switching had been done at the model.

The delay in signal response related to tube length and pressure differential was evaluated both in the laboratory and after the instrument was installed in the tunnel. System response under varying conditions in the laboratory was typically as shown in figure 8, which depicts the concentration gradient pulse of the mass spectrometer resulting from injecting 1.0 mℓ of neon into a 15.2 m (50 foot) length of 1.65 mm (.065 in) id tubing. This response was found to be relatively constant over a wide range of test conditions, and similar results were obtained when delays were determined with the instrument in the tunnel.

The mass spectrometer used was a small, computer controlled, quadrupole system developed by the Analog Technology Corp., Irwindale, California, for an interagency program, for which NASA had technical and contractual responsibility. The instrument (Wood and Yeager, 1980) is a trace gas analyzer, figure 9, designed to continuously sample ambient air, at or below atmospheric pressure, and to analyze the stream for minor constituents. The instrument can be directed to scan over all or a portion of the mass range of 1-200 amu, to monitor a single mass as a function of time, or to automatically analyze for up to 40 selected trace constituents and to report their presence

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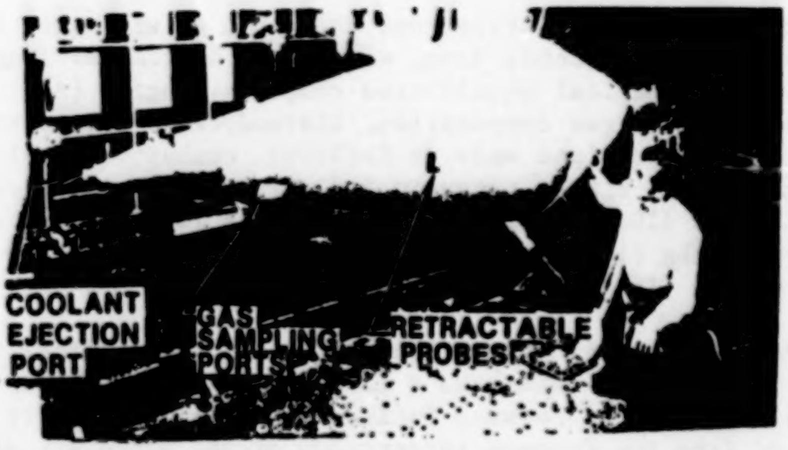
COOLANT
EJECTION
PORT
GAS
SAMPLING
PORTS
RETRACTABLE
PROBES

Figure 6.- Model used for the nitrogen film cooling experiments. The nitrogen ejecting ogive nose tip is shown on the 12.5° half-angle conical model and sampling ports are indicated. The model is in the test position.

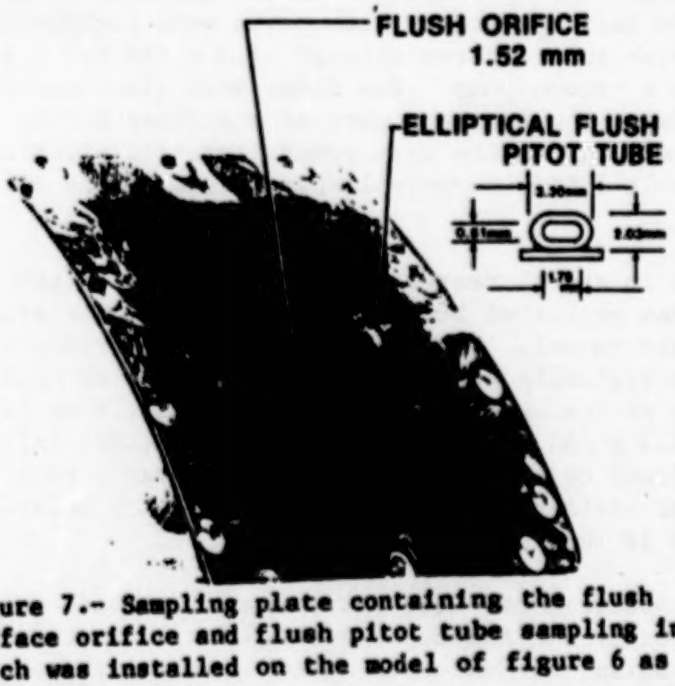
FLUSH ORIFICE
1.52 mm
ELLIPTICAL FLUSH
PITOT TUBE
3.30mm
0.81mm
2.03mm
1.78

Figure 7.- Sampling plate containing the flush surface orifice and flush pitot tube sampling inlet which was installed on the model of figure 6 as indicated.

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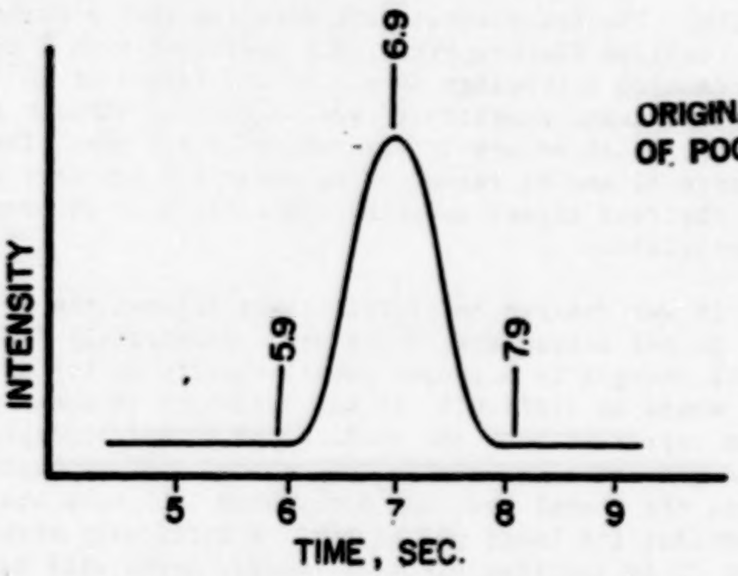

Figure 8 .- Typical laboratory single mass peak intensity response with time for a gas sample injected into a port connected to the mass spectrometer by 15.2 m of 1.65 mm id tubing.

Figure 9 .- The small computer quadrupole mass spectrometer system used in the 8-foot HTT experiments.

in concentration units. The ion currents are detected with a channeltron electron multiplier (Galileo Electroptics), and amplified with a current-to-frequency convertor (Analog Technology Corp.) having ranges of 10^{-14}, 10^{-13}, and 10^{-12} amps/Hz. Instrument sensitivity was determined through a mass scan of atmospheric krypton, which occurs at approximately 1.1 ppm. The minor isotope peaks at masses 82 and 83 representing about 120 ppb were easily measurable, and the observed signal to noise indicated that concentrations as low as 40 ppb are detectable.

In these tests it was desired to differentiate between the nitrogen cooling gas and the tunnel atmosphere, which was approximately 72% nitrogen. Since measuring small changes in nitrogen peak intensity on top of the already large existing peak would be difficult, it was necessary to use a measured amount of tracers to represent both the coolant and tunnel atmosphere. To eliminate effects of gas reactions within the system, 0.9% atmospheric argon was used to represent the tunnel gas, and a measured 1-3% neon mixture in the coolant nitrogen provided its inert gas tracer. A difficulty with this selection is that at 70 ev ionizing electron energy, argon will have a doubly-charged peak appearing at an exact mass of 19.9812 due to the loss of 2 electrons. Singly charged neon has an exact mass of 19.9924, requiring a resolving power of 1 part in 1778 to separate the two, which exceeds the capability of the instrument. The doubly-charged argon will disappear when the ionizing electron energy is lowered to about 43 ev, while the singly-charged argon and neon peak intensities are reduced by smaller amounts. By operating the mass spectrometer at an ionizing electron energy of the 35 ev, the interference was removed and the measured neon/argon ratios were indicative of concentrations of coolant and tunnel gas at the mass spectrometer inlet.

The mass spectrometer data was taken over the whole sequence of tunnel operations starting shortly before the tunnel startup began. Thus, data were obtained over the operational sequence of events in the tunnel which produced the gaseous environments and transitions to which the mass spectrometer sampling inlets on the model were exposed.

The data obtained followed the test sequence with a lag time appropriate to the pressure drop across the transport tube. Due to a suspected problem with the mass spectrometer ion pump there appeared to be an anomalously high Ne background in the mass spectrometer data taken during the last 3 runs in the 8 foot HTT using Ne seeded coolant N_2 which made those data questionable for quantitative measurements but produced trends which are qualitatively valid and consistent with an earlier run. The mass spectrometer response data reflects the concentration of the constituent being measured. It also tracks pressure changes to the extent that the total signal intensity depends on pressure but the relative ion current intensity reflecting composition of the gas in the ion source does not. This requires that the ion source response is linear for all species over the pressure range of interest. If this is the case, changes of concentration of a species or in relative concentration of one species to another becomes a simple matter of obtaining a ratio of the appropriate peak intensities. As will be seen below in the discussion of results, the Ar intensity data traced the changes in tunnel pressure quite well. For the nitrogen film cooling experiment, the ratio of the intensity of neon at mass 20 to argon at mass 40 was used as a measure of the mixture ratio of cooling nitrogen to tunnel test gas at the model surface where sampled.

Data required to calculate the mixing ratio of cooling N_2 to air by this method are: the sensitivities of the instrument for Ne and Ar at mass 20 and 40 respectively, the concentration of Ne (mole fraction, N_{Ne}) tracer in the cooling N_2, the concentration of Ar (mole fraction, N_{Ar}) in the tunnel gas and the ratio of the mass spectrometer sensitivities of Ar (40) to Ne (20), (S_{40}/S_{20}), for standard mixtures of the two. The mixing ratio of cooling nitrogen to tunnel gas is then given by:

$$\frac{n_{NC}}{n_{TG}} = \frac{I_{20}}{I_{40}} \times \frac{S_{40}}{S_{20}} \times \frac{N_{Ar}}{N_{Ne}}$$

and the mole fraction of coolant nitrogen by

$$N_{NC} = \frac{n_{NC}}{n_{NC} + n_{TG}}$$

where n is the number of moles, S is the sensitivity in hertz/mole, I is the mass spectrometer response in hertz and N is the mole fraction. The subscript NC stands for coolant nitrogen and TG for tunnel test gas.

Figures 10, 11, and 13 are typical of runs that were made and show the trends which are significant in the appraisal of the experiments for planning the ongoing development program. Figure 10 shows the mass spectrometer response for N_2 (mass 28) and Ar (mass 40) sampled through the flush orifice with the model in the test section. Nitrogen was ejected at 4.5 lb/sec from the nose tip, however, the tunnel was otherwise inactive and open to the atmosphere. The curves for N_2 and Ar show the change in concentration with time when sampled at the orifice site at constant pressure. The changing ratio of N_2 to Ar responses indicated that N_2 concentration in the test chamber was increasing relative to Ar and the air it represents.

Figure 11 shows single mass scan intensity vs time data for mass 44, CO_2, sampled through the flush orifice at 10° angle of attack. Tunnel/model data plotted in this figure are test section pressure, P_{TS}, pressure at sampling orifice, P_o, combustor temperature, T_c, and combustor pressure, P_c. Events in the tunnel operation indicated along the time axis of the figure by letters include (A) ejectors on (B) combustor on, (C) model in, (D) model out, (E) combustor off, (F) N_2 purge of fuel line, and (G) ejectors off. The data indicates, as seen on the figure, that under the conditions of this test and the sampling system, the CO_2 concentration increased somewhat steadily from the time the combustor came on (B) to a peak after about 4 seconds in the test stream (C) to (D) and then decreased until the combustor was shut off (E) right after the model went down (D). When the fuel lines were purged with N_2 (F), the CO_2 intensity rose sharply to about twice that of the of the previous peak, peaked again to a higher level yet about the time the ejectors went off (G) and then decayed to a low value as the pod came up to atmospheric pressure. Other runs under different test conditions for which the CO_2 mass 44 peak was tracked showed some of the same features but with variations. These kinds of results require a more thorough investigation into sampling techniques, instrument effects, and the chemistry which may be taking place.

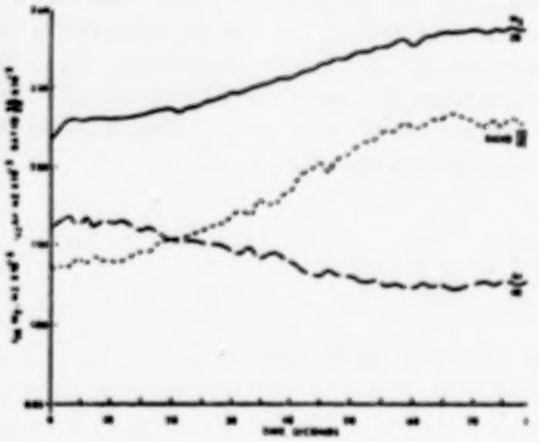

Figure 10.- Mass spectrometric intensity-time plots of N_2 at mass 28, Ar at mass 40, and intensity of mass 28/40 when model was in test position in the tunnel test section without flow and nitrogen gas was being blown from the nose tip at a rate of 4.5 lb/sec. Pressure at the orifice was constant at 14.7 psia.

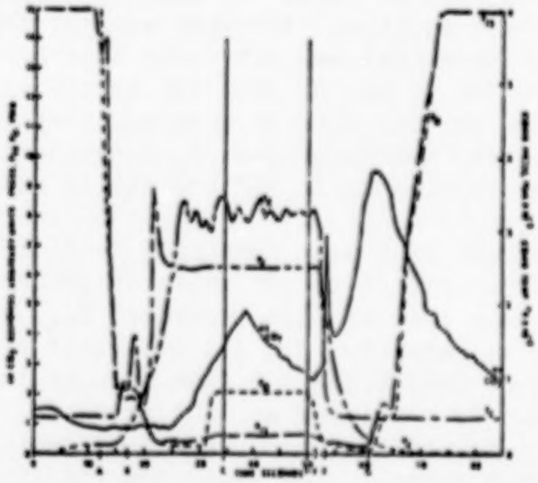

Figure 11.- Mass spectrometric data for the CO_2 mass 44 peak sampled by the model surface orifice inlet and tunnel data for a run where the blunt nose model was at a 10° angle of attack and the tunnel was being operated at a combustor temperature T_c of about 1780° K and combustor pressure P_c of 2500 psia. Model was in test stream for 15 sec. Tunnel events indicated are: A ejector pumps on; B, combustor startup; C, model in test stream; D, model out; E, combustor off; F, N_2 purge of fuel line; G, ejector pumps off. P_{TS} is pressure in test section, P_o is pressure at orifice.

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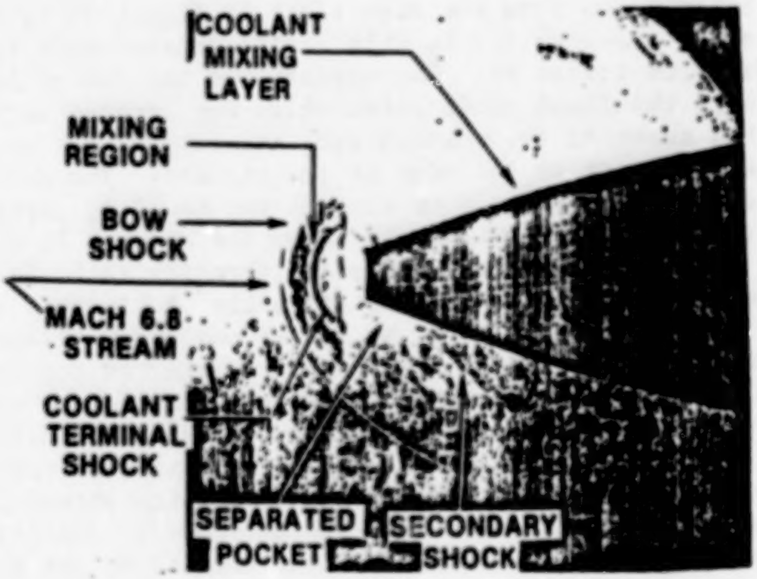
COOLANT
MIXING
LAYER
MIXING
REGION
BOW
SHOCK
MACH 6.8
STREAM
COOLANT
TERMINAL
SHOCK
SEPARATED
POCKET
SECONDARY
SHOCK

Figure 12 .- Shadowgraph of typical tunnel run in which coolant nitrogen is being ejected from nose tip showing the interaction of the flows.

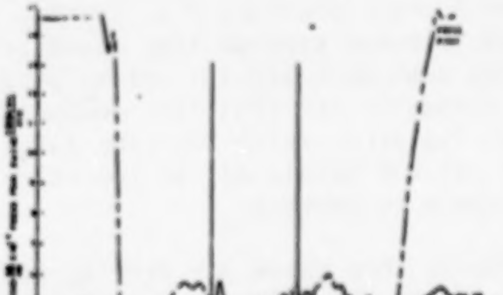

Figure 13 .- Mass spectrometric data for the Ne mass 20 and Ar mass 40 peak intensities continuously sampled from the flush pitot inlet and the derived coolant N_2/tunnel air mixture data along with tunnel data for a film cooling run using Ne seeded N_2 ejected from nose tip at rate of 1.2 lb/sec. Model was at a 6° angle of attack and combustor temperature was about 1940°K at 2500 psia. Tunnel events indicated are: A, ejector pumps on; B, combustor startup; C, model in stream; D, model out; E, combustor off; F, ejector pumps off.

Figure 12 is a typical shadowgraph of the model in the tunnel stream with coolant N_2 being blown from the nose tip. In figure 13 is shown typical data as a function of time for the N_2 film cooling experiments in which the coolant N_2 was seeded with tracer Ne. The species for the run of figure 13 were sampled through the flush pitot inlet which was located farther downstream on the model than shown in the shadowgraph, actually almost twice the distance from the ejection port to the edge of the picture. The mass spectrometer data time coordinates were adjusted to account for sampling lagtime as they were throughout these studies. Figure 15 shows the Ne mass 20 and Ar mass 40 peak intensities throughout the run, the peak intensity ratio for the Ne/Ar (20/40), the calculated mixing ratio of cooling N_2 to test gas (air) and the pressure at the pitot inlet. The Ne seeded coolant (0.42%Ne) N_2 flow was initiated and regulated before the tunnel was started and continued until after the run was over. For the run, the AOA was 6°, the cooling N_2 flow rate was 1.2 lb/sec, total gas temperature about 1889°K, combustor pressure was 2500 psia. The qualitative interpretation of this mass spectrometer data and of 3 other runs with Ne seeded N_2 coolant gas which showed the same trends indicate that the seeded coolant gas was detected in relatively substantial amounts in that part of the boundary layer sampled by the pitot on the model surface.

The following I_{20}/I_{40} trends were exhibited for all 4 runs: in pod at atmospheric pressure before ejector on (A) and combustor start-up (B), rather steady low value; after ejector on and pressure lowered to about 2 psia and combustor on, moderately sharp rise peaking just before model insertion (C); while in test stream with pitot pressure 3 to 5 psia, slight decrease to shallow valley and then increase towards time model removed from test stream (D); after model out and combustor off (E) and N_2 purge, continued increase, peaking about time of combustor off (E); from combustor off until ejector off (F) with pressure about 0.5 psia, ratio declines slightly and drops off sharply at ejector off (F) and levels off at low value after coolant Ne/N_2 is shut off and system returns to ambient.

These changes indicate that there are varying ratios or mechanisms of mixing in the area sampled by the inlets or possibly different sampling depths within a laminar boundary layer with a concentration gradient. Experiments related to sampling parameters are needed both in the laboratory and in the facility. Laboratory investigations are presently underway to quantitatively determine the effects of sampling tube length on mass spectrometer measurements of known mixtures of Ne, Ar, and N_2 and of CO_2, H_2O and air. Experiments are being developed to measure the gas composition in the 8' HTT with pitot probes and flush orifices and with minimum practical length sample transport tubes. Gases will be sampled at several points; in the pod, in the test stream upstream and downstream of a model with and without the model in the stream; and at the center and on the wall of diffuser section behind the model.

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APPLICATION NO. 2 - LARGE APERTURE ANTENNA RANGE, W. L. GRANTHAM, LaRC

ELECTROMAGNETIC EXPERIMENT CONCEPTUAL DESIGN

OUTLINE

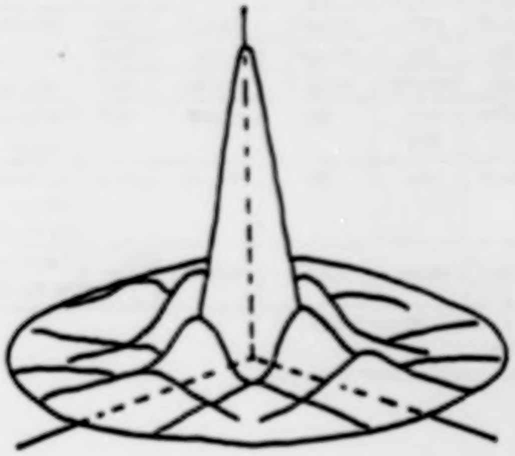
- EXPERIMENT REQUIREMENTS
- MEASUREMENT TECHNIQUES
  - CO-ORBITER TARGETS
  - CELESTIAL SOURCES
  - GROUND BASED SYSTEMS
- FLIGHT HARDWARE DESIGN
- PERFORMANCE SUMMARY
- CONCLUSIONS

ELECTROMAGNETIC EXPERIMENT REQUIREMENTS

EXPERIMENT		MEASURED PARAMETER[1]	TEST CONDITIONS
1	PATTERN DETERMINATION	ANTENNA PATTERN	•FULL SUN •EDGE-ON SUN •NO SUN
2	BORESITE TRANSIENT	BORESITE GAIN AND ANGLE	
3	THERMAL TRANSIENT		•NEAR OCCULTATION •EDGE-ON TO FULL SUN
4	APERTURE ILLUMINATION	ANTENNA PATTERN	•NO SUN •VARIABLE ILLUMINATION TAPER
5	SURFACE ROUGHNESS EFFECTS		•NO SUN •D/λ = 333, 2173 •SURFACE ERROR $\lambda/59$, $\lambda/9$
6	INTERMODULATION[2]	SPURIOUS FREQUENCIES	•NO SUN •FULL SUN

NOTES: [1] OPTICAL MEASUREMENT OF ANTENNA SURFACE AND FEED REQUIRED FOR ALL EXPERIMENTS
[2] NOT PART OF OF BASELINE

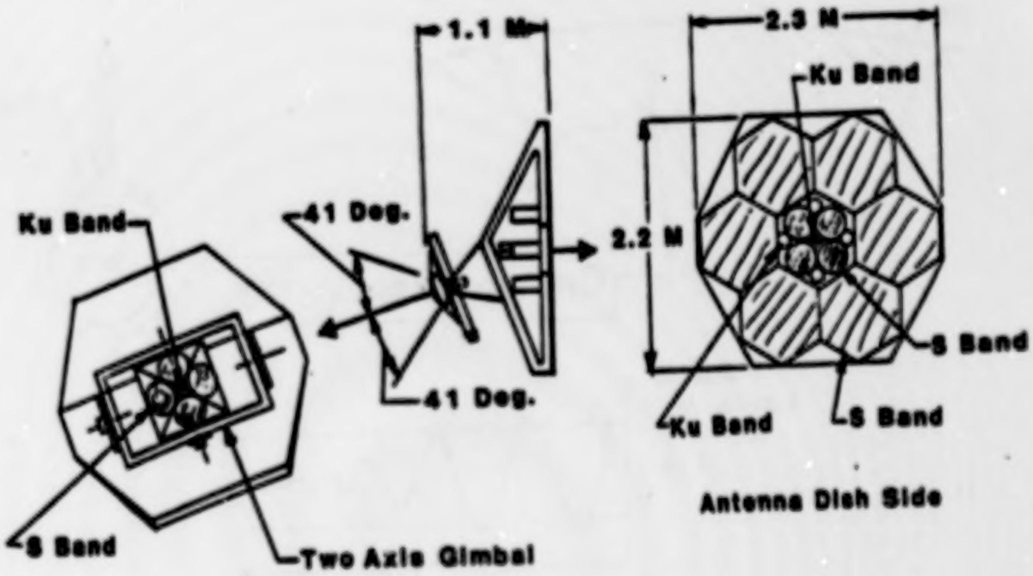
ANTENNA MEASUREMENT REQUIREMENTS



PARAMETERS

- BORESITE GAIN, ANGLE
- NEAR-IN SIDELOBES
- HEMISPHERICAL SCAN
- CROSS POLARIZATION
- RASTER SCAN

FEED PANEL CONFIGURATION


1.1 M
2.3 M
Ku Band
41 Deg.
2.2 M
Ku Band
S Band
41 Deg.
Ku Band
S Band
S Band
Two Axis Gimbal
Antenna Dish Side

MEASUREMENT TECHNIQUE SUMMARY

JUNE 15, 1983

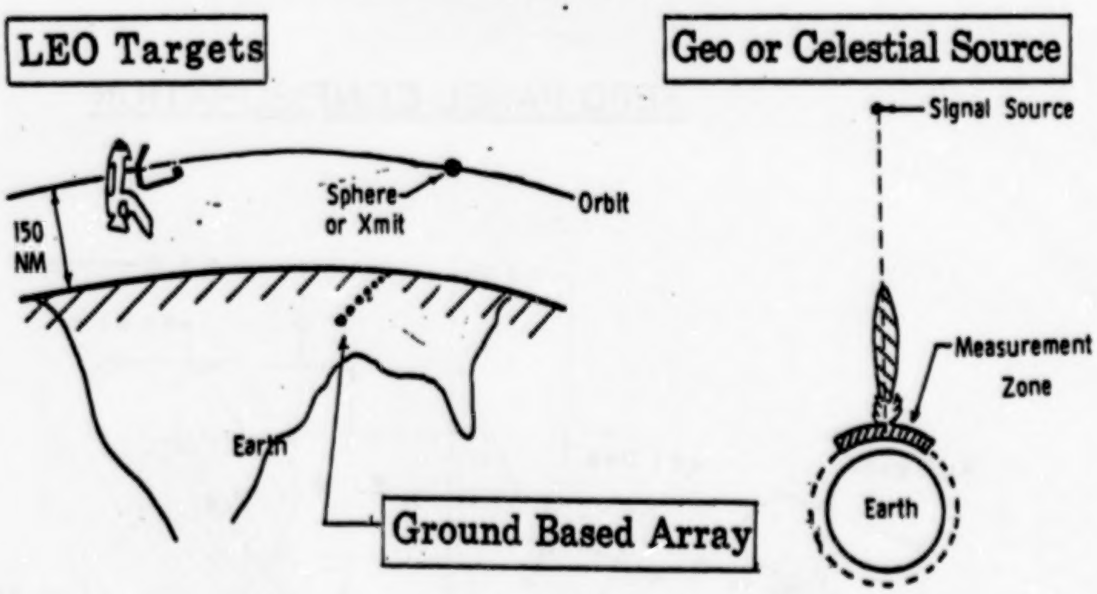
TECHNIQUE		BORESITE TRANSIENT	BORESITE STATIC	NEAR-IN SIDELOBES	HEMISPHERICAL SCAN	CROSS POLARIZATION	RASTER[3] SCAN	COMMENTS
		ANTENNA PARAMETERS						
CO-ORBITER	LEO-SPHERE	GOOD	EXCELLENT	POOR[1]	MARGINAL[1]	EXCELLENT	POOR[2]	RASTER SCAN IS LIMITED BY SETTLING TIME OF STRUCTURE
	LEO-XMIT	EXCELLENT	GOOD	GOOD	EXCELLENT	GOOD	POOR[2]	
	GEO-XMIT	EXCELLENT	GOOD	EXCELLENT	EXCELLENT	MARGINAL	POOR[2]	
CELESTIAL SOURCES	RADIO STARS	GOOD	MARGINAL	NEEDS STUDY	GOOD	MARGINAL	POOR[2]	•COMPLEX HARDWARE •TECHNICAL ISSUES
GROUND BASED SYSTEMS	ARRAY	POOR	MARGINAL	GOOD	GOOD	MARGINAL	EXCELLENT	•LIMITED TEST TIME •HIGH COST •NO FULL SUN
	SINGLE STATION	POOR	POOR	MARGINAL	MARGINAL	MARGINAL	POOR	•LIMITED TESTING TIME •NO FULL SUN

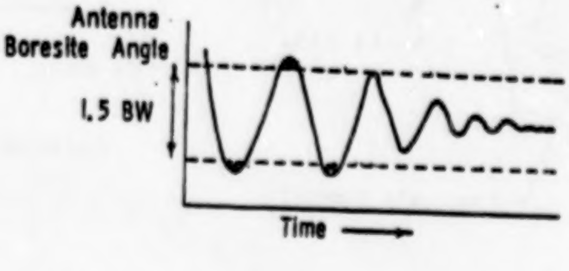
NOTES: [1] MAY BE IMPROVED WITH LARGER TARGET (INFLATABLE-TETHERED SPHERE)

[2] MAY BE IMPROVED IF SETTLE TIME IS SHORT

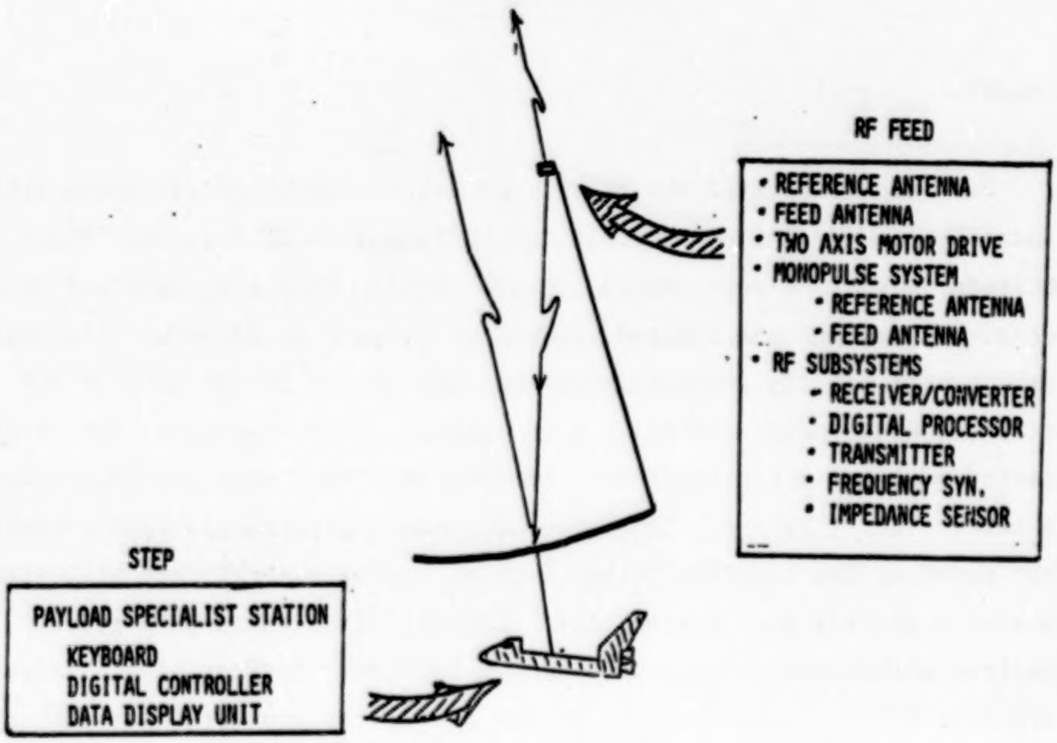
[3] ALSO PROVIDES MEASUREMENT OF REFLECTOR CONTOUR (HOLOGRAPHIC TECHNIQUE)

ANTENNA MEASUREMENT TECHNIQUES


LEO Targets
Geo or Celestial Source
Signal Source
Sphere or Xmit
Orbit
150 NM
Measurement Zone
Earth
Earth
Ground Based Array



BASELINE FLIGHT HARDWARE



RF FEED

- REFERENCE ANTENNA
- FEED ANTENNA
- TWO AXIS MOTOR DRIVE
- MONOPULSE SYSTEM
    - REFERENCE ANTENNA
    - FEED ANTENNA
- RF SUBSYSTEMS
    - RECEIVER/CONVERTER
    - DIGITAL PROCESSOR
    - TRANSMITTER
    - FREQUENCY SYN.
    - IMPEDANCE SENSOR

STEP

PAYLOAD SPECIALIST STATION
KEYBOARD
DIGITAL CONTROLLER
DATA DISPLAY UNIT

CONCLUSIONS

JUNE 15, 1983

- MEASUREMENT REQUIREMENTS CAN BE SATISFIED USING SEVERAL DIFFERENT APPROACHES
- SHORT SETTLE TIME (CONTROLLED OR NATURAL) COULD PROVIDE IMPORTANT RASTER SCAN PATTERNS AND RF DETERMINED REFLECTOR CONTOUR
- CELESTIAL SOURCES APPROACH ALSO COULD PROVIDE VLBI AND PBMR EXPERIMENT DEMONSTRATION

N85-20373

APPLICATION NO. 3 - USING TETHERS FOR ATTITUDE CONTROL, R.M. MULLER, GSFC

SUMMARY

Past application of the gravity gradient concept to satellite attitude control produced attitude stabilities of from 1 to 10 degrees. These attitude excursions were caused by small environmental torques and orbital eccentricities and the limited capability of passive dampers. The satellite members were rigidly interconnected and any motion in one part of the satellite would cause motion in all members. This experience has retricted gravity gradient stabilization to applications that need attitude stability no better than 1 degree. This note proposes a gravity gradient technique that combines the flexible tether with an active control that will allow control stability much better than 1 degree. This could give gravity gradient stabilization much broader application. In fact, for a large structure like a Space Station, it may become the preferred method!

This note proposes two possible ways of demonstrating the technique using the Tethered Satellite System (TSS) tether to control the attitude of the Shuttle. Then a possible Space Station tether configuration is shown that could be used to control the initial Station. It is then shown how the technique can be extended to the control of Space Stations of virtually any size.

SHUTTLE ATTITUDE STABILITY WITH THE PRESENT TSS

When one considers the TSS as presently conceived, the attitude of the Shuttle is not particularly controlled, but rather it is allowed to follow the motions of the Satellite. The resulting Shuttle attitude motion is quite stable because the attachment point of the tether is on the end of a boom well above the center of gravity (CG) of the Shuttle. Figure 1-B illustrates the nominal attitude of the Shuttle when the TSS is aligned with the local vertical. (The TSS is shown above the Shuttle to eliminate drag effects from consideration in this discussion. The conclusions will not change if the inverted, high drag configuration is used, however.) Figure 1-A illustrates the pitch down torques that would exist at the Shuttle when the TSS gets ahead of the Shuttle and the Shuttle was able to maintain its nominal attitude. Clearly, if the Shuttle is not to expend propellent, it must respond to this torque. Similarly, Figure 1-C illustrates a pitch up torque when the TSS gets behind the Shuttle. The fore/aft motion of the TSS is a perfectly normal motion that is caused primarily by orbit eccentricity and drag effects. The motion can be made as small as a few degrees, but not easily eliminated. Figure 1 is drawn as though the Shuttle's orbital plane is the plane of the paper and the Shuttle's pitch axis is perpendicular to the orbit plane.

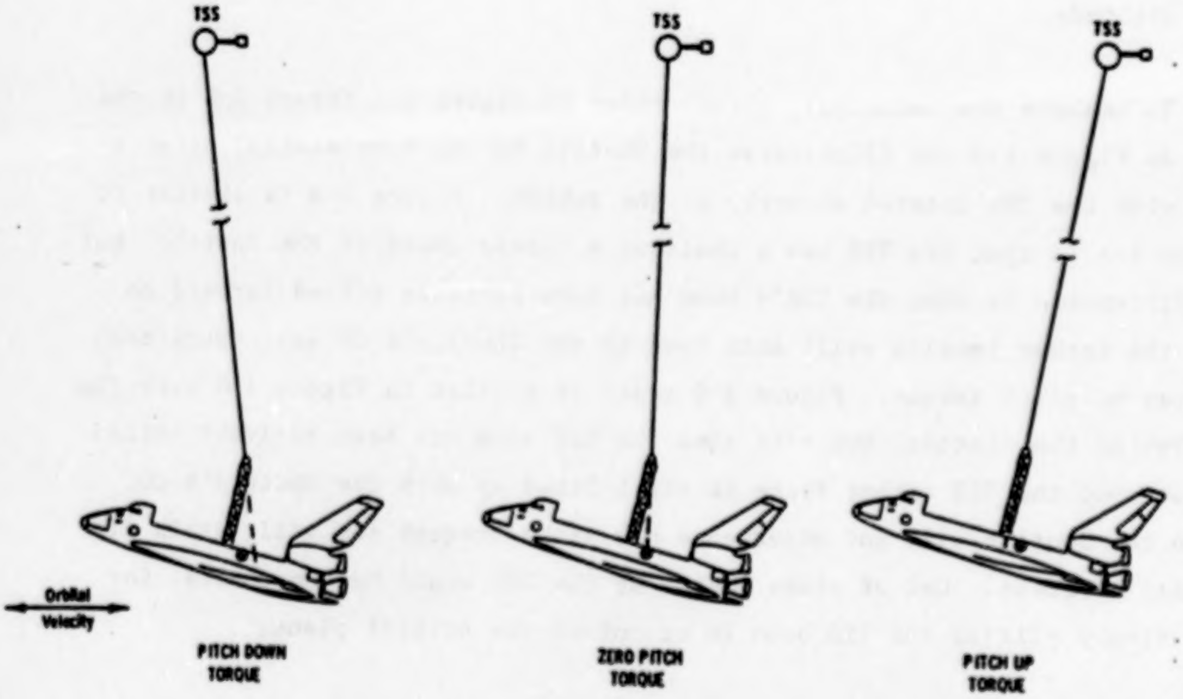


FIG.1- SHUTTLE PITCH TORQUES CAUSED BY TSS MOTION

The TSS can also move out of the orbital plane. Such motion simply causes The Shuttle to roll. These pitch and roll motions will not affect the operation of the TSS or the Shuttle.

If the Shuttle's long axis is aligned with the velocity vector, it is also aligned with a natural yaw equilibrium. This is the orientation used in all figures in this paper. If this nominal attitude is used for the proposed demonstrations, very little fuel will be required by the Shuttle to maintain yaw control.

SHUTTLE ATTITUDE CONTROL DEMONSTRATION USING THE TSS

A future flight of TSS could be used to not only perform its regular mission, but to demonstrate control of the Shuttle's attitude using the TSS tether tension to provide the necessary torques. Once this technique is demonstrated, it could be extended to control the Space Station pitch and roll attitude.

To explain the technique, please refer to Figure 2. Figure 2-B is the same as Figure 1-B and illustrates the Shuttle in the same nominal orientation with the TSS located directly at the zenith. Figure 2-A is similar to Figure 1-A in that the TSS has a position a little ahead of the Shuttle, but the difference is that the TSS's boom has been actively tilted forward so that the tether tension still acts through the Shuttle's CG and, therefore, creates no pitch torque. Figure 2-C again is similar to Figure 1-C with the TSS behind the Shuttle, but this time the TSS boom has been actively tilted aft so that the TSS tether force is still lined up with the Shuttle's CG. Again the Shuttle will not experience any pitch torques and will retain its nominal attitude. Out of plane motion of the TSS would be compensated for by actively tilting the TSS boom in or out of the orbital plane.

Note that by tilting the nominal boom position from that shown in Figure 2-B, the Shuttle may be held at some other attitude. The range of nominal attitudes is limited by the placement of the TSS pallet in the

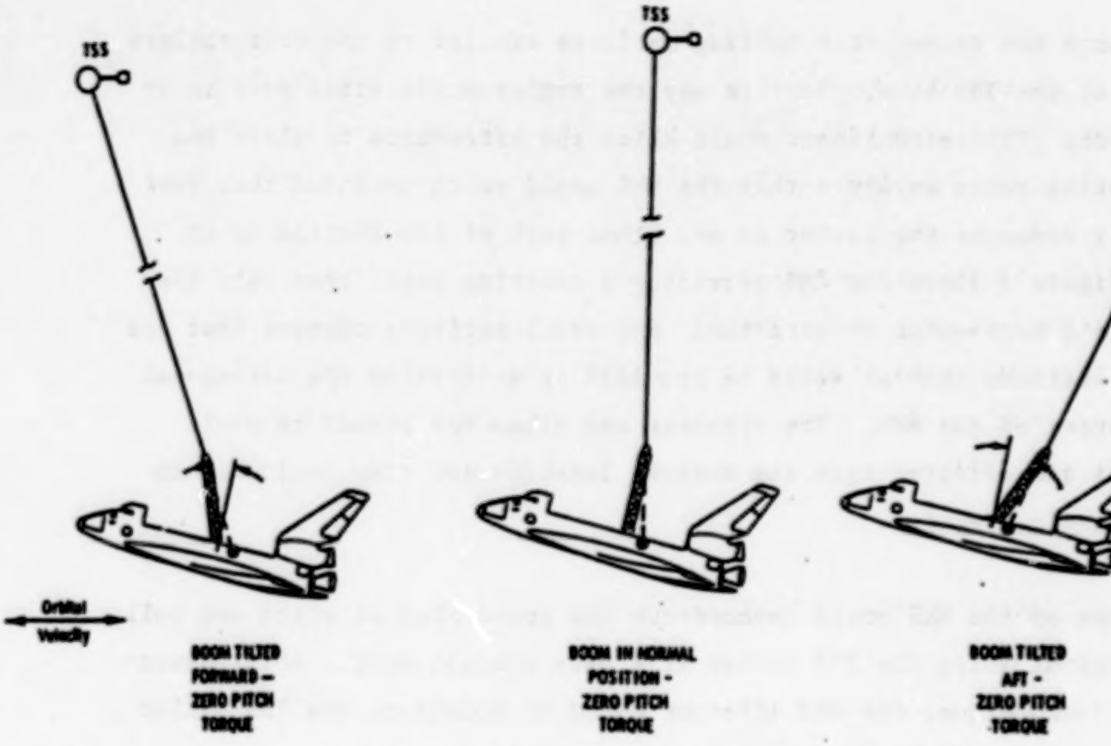

TSS
TSS
TSS
Orbital Velocity
BOOM TILTED FORWARD — ZERO PITCH TORQUE
BOOM IN NORMAL POSITION - ZERO PITCH TORQUE
BOOM TILTED AFT - ZERO PITCH TORQUE

FIG.2- TORQUING OF SHUTTLE CAN BE MADE ZERO BY TILTING BOOM

Shuttle's bay and the total range of motion built into the boom's two-axis drive mechanism. If the TSS pallet was mounted in the bay over the Shuttle's CG, a horizontal Shuttle orientation would be nominal.

To implement this demonstration, the TSS boom mechanism would require modification from its present configuration in order to add a two-axis gimbal at its base.

AN ALTERNATIVE DEMONSTRATION USING THE RMS TO MOVE THE TETHER

An alternate way of demonstrating the control of the Shuttle's attitude using the TSS tether would be to use the Remote Manipulator System (RMS) to displace the tether's reaction point to other locations relative to the Shuttle's CG. One possible reaction point is illustrated in Figure 3. For this purpose, a special RMS end effector would be used. This end effector

would surround the tether with rolling surfaces similar to the exit rollers on the end of the TSS boom. In this way the tether could still move in or out as before. This arrangement would allow the astronauts to place the tether reaction point anywhere that the RMS could reach provided that that point didn't endanger the tether or any other part of the Shuttle or its payload. Figure 3 shows the RMS providing a reaction point that puts the Shuttle into a horizontal orientation. Any small attitude torques that are needed for attitude control would be provided by activating the orthogonal wrist actuators of the RMS. The shoulder and elbow RMS actuators would position the end effector into the desired location and then be locked in place with their brakes.

This use of the RMS could demonstrate the principles of pitch and roll attitude control using the TSS tether at a very nominal cost. After demonstrating the technique, the end effector could be stowed on the TSS pallet and the RMS then would be available for other duties.

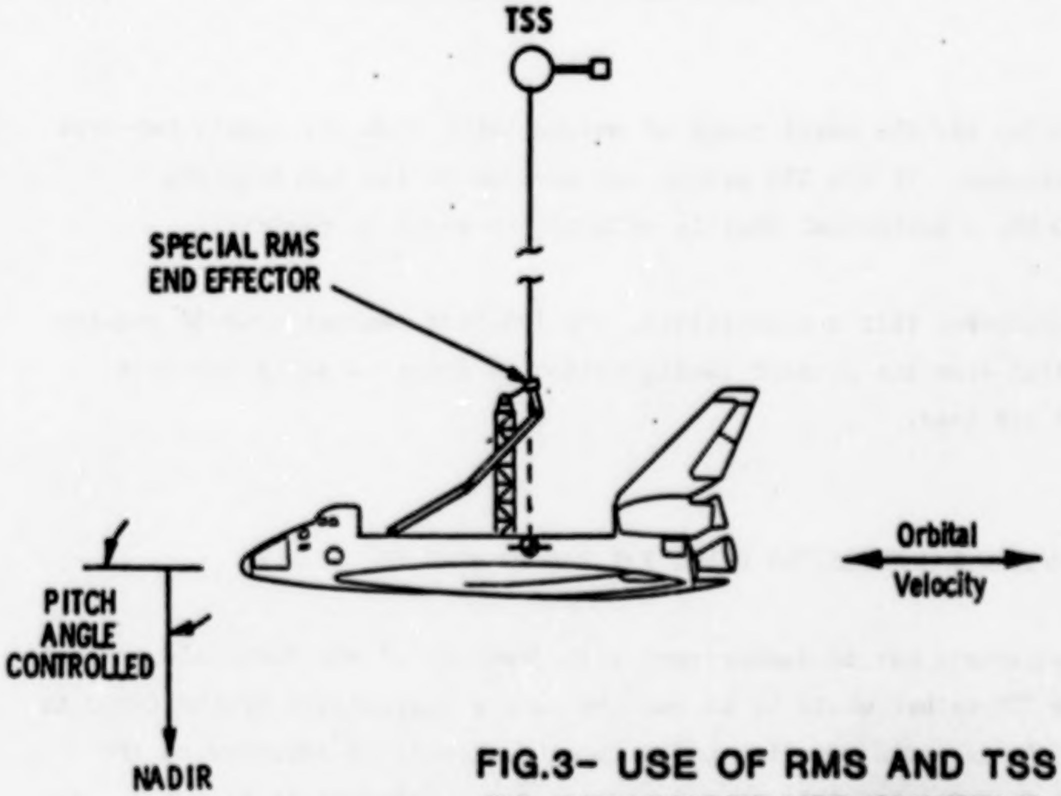


FIG.3- USE OF RMS AND TSS TO DEMONSTRATE SHUTTLE ATTITUDE CONTROL

SPACE STATION ATTITUDE CONTROL USING TETHERS

Let's turn our attention to the attitude control of a Space Station. It will start out small and could grow to be a massive structure. It is clear that the Station's CG and inertias will change with time because the Shuttle will dock/undock with it, new Station modules will be added, OTV's will be launched and recovered and fuels will be transferred. Surely this will be a frustrating object to keep stable in attitude. In fact, as parts are added to (and removed from) the Space Station, it will be nearly impossible to maintain it in a balanced configuration to minimize gravity gradient torques. (To balance a Station so as to minimize gravity gradient torques, the moments of inertia in all axes must be equal.) Torques exerted by this unbalance could be the major source of attitude disturbance and will probably require expenditure of fuel to counteract. For instance, many artist's versions of the Space Station show the major axis (highest inertia axis) of the Station aligned with the velocity vector. This is necessary to give minimum drag, but it is an unstable equilibrium state for gravity gradient. If active attitude control were lost, the Station would tend towards the stable gravity gradient orientation with the long axis aligned with the local vertical.

So how can tethers help? First imagine that the Space Station is composed of two parts separated by a 2 km long tether. One part could be the usual Space Station module just the same as the artist shows and the other part could be the External Tank (ET) that was used for that Shuttle launch. Figure 4 illustrates this configuration. (For this discussion, the ET serves only as a ballast weight, but obviously it could be used for other functions such as a hanger for protecting OTV's, etc.) At the ET end, the tether is terminated in a yoke so that the ET can be maintained in a minimum drag orientation. At the Space Station, the tether terminates in a reeling mechanism that is attached to an X-Y carriage mechanism. As the CG of the Station moves fore or aft, or as the ET moves fore or aft, the carriage would move fore or aft to maintain the desired Station's attitude. Similarly, roll attitude could be maintained by moving the carriage to the left or right. This would be done in a closed loop fashion using the same type of control signals that would drive a conventional control moment gyro (CMG)

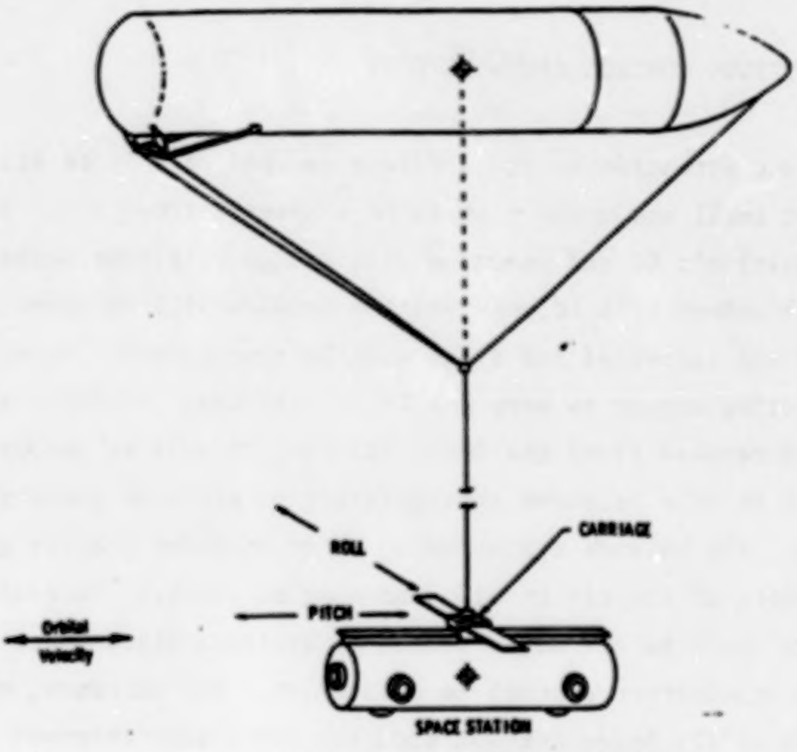


FIG.4–INITIAL SPACE STATION USING A TETHER FOR ATTITUDE CONTROL

system. Note that stable Space Station orientations other than horizontal are possible with this configuration. For instance, controlled pitch up or down by 70 degrees and/or roll right or left of about 50 degrees are available with the configuration illustrated. (In Figure 4, the size of the track and carriage mechanism is very much exagerated in order to be clearly seen in the drawing.)

SPACE STATION GROWTH

Suppose that the original Station was to be expanded by the addition of another module. The same kinds of reeling and translation mechanisms would be installed on this new module. Again, the ET used for this launch would be deployed as additional ballast mass. To achieve this double size configuration, the Shuttle would dock with the original Space Station at a docking port and the tether system could hold the Station with attached Shuttle and ET in a stable attitude. This will allow the removal of the new payload from the cargo bay and facilitate transfer of astronauts between the Station and the Shuttle. Such a docking is illustrated in Figure 5. The new module would then be removed from the cargo bay and attached to the original Space Station at one end. The new ET would then be detached from the Shuttle and reeled out to the location of the old ET using the new tether reeling mechanism and carriage. It would use the original tether as a guide. The new ET would then be mechanically linked up to the old ET. The tethers can now hold the entire assemblage in the horizontal position because the CG of the two Station modules and the Shuttle would be between the two tethers and their carriage mechanisms. The final Space Station configuration is shown in Figure 6 without the Shuttle attached.

The second tether system provides redundancy against the remote possibility of tether breakage. It also provides multiple means of controlling the Station's attitude and thus provides for mechanism redundancy. Pitch and roll can be controlled by either one or both of the traveling carriages. Attitude can be maintained even if one carriage doesn't work. Also, the relative length of the two tethers can be controlled by either of the two reeling mechanisms. The Station's attitude would be controlled by the position of carriage mechanisms and the tether lengths would control the attitude of the ET's.

The Station's yaw control would be maintained by a CMG as in present Station concepts. If the nominal orientation of the Station is with its long axis in the orbit plane, a natural yaw equilibrium will be operating. This will minimize the demands on the CMG.

SPACE STATION GROWTH BEYOND TWO MODULES

To get a feeling for the magnitude of the tether forces, suppose that a maximum Station consists of eight station modules and eight ET's for a total mass of about 450 Mg (990,000 pounds). If the total tension between the Station and the eight ET's was taken by a single tether, it would experience only about 900 N (200 pounds) force. Even the TSS tethers have higher breaking strengths than this! Because the loads for even a large

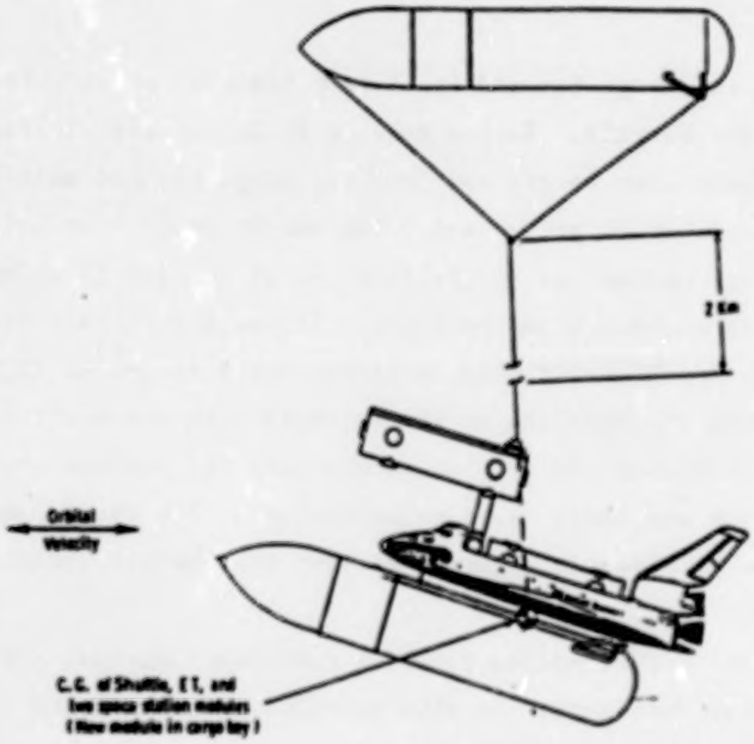

2 Km
Orbital
Velocity
C.G. of Shuttle, E.T. and
two space station modules
(New module in cargo bay)

FIG.5-SHUTTLE WITH
NEW SPACE STATION MODULE
AND ET DOCKED TO
ORIGINAL SPACE STATION

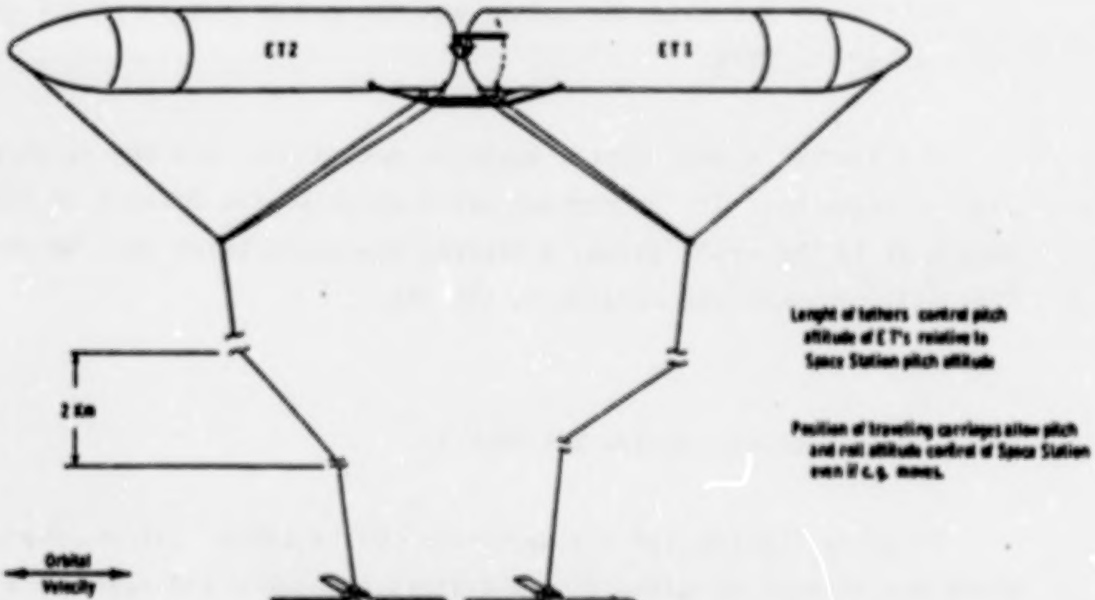

ET 2
ET 1
Lenght of tethers control pitch
attitude of E T's relative to
Space Station pitch attitude
Position of travelling carriages allow pitch
and roll attitude control of Space Station
even if c.g. moves.
2 Km
Orbital
Velocity
ADDED SPACE STATION COMPONENT
ORIGINAL SPACE STATION

FIG.6-TWO MODULE
SPACE STATION WITH
TETHER ATTITUDE CONTROL

Station are small, it can be presumed that the original tethers would be grossly oversized for the initial system so that modules 3 through 8 can be added to the Space Station without the expense of adding additional tethers or carriage mechanisms. All that is required is that as Station modules are added, the CG of the new Station configuration or of the ET's be within the range of the two tether carriages and two yokes.

CONCLUSION

The tether tension that exists between two bodies in a stable gravity gradient orientation can be used for the independent orientation of each body in pitch and roll. This could be demonstrated using the TSS with either an articulated mast or the RMS with a special end effector. A successful demonstration using the TSS would allow this concept to be considered for the Space Station. The Station could be allowed to grow to very large proportions and still be precisely controlled. The loading in the tethers could be kept low so that tether mass including a large strength safety factor would not be a constraint.

APPLICATION NO. 4 - ORBITAL WAKE EFFECTS, A. KONRADI & R.J. JOST, JSC

BACKGROUND

A large body (Shuttle, space station, large structures, etc.) moving in LEO sweeps up the tenuous medium consisting of residual neutral gas and ionospheric ions to produce a void in its wake. The void is eventually filled with diffusing neutrals and ions and its length is determined by their temperature. As an example, the shape of the wake behind a 10 m diameter sphere is roughly conical and for an ion temperature of 1500° K, its apex would lie 62 m behind the sphere. Thus, a smaller object co-orbiting with the large body and positioned in its wake would not be exposed to the ionospheric plasma.

Let us now look at the following situation: The Shuttle is in low polar orbit and approaching the auroral zone on the night side of the Earth. Its orientation is such that the Z (yaw) axis lies along the velocity vector. Suppose we have a relatively small object, be it a sub-satellite or a free flying astronaut in a MMU, located above the cargo bay. Just at that time the Shuttle Orbiter is passing through an electron precipitation which is producing a beautiful auroral display at a lower altitude. What happens? In physical terms the Orbiter is being bombarded by the beam of energetic electrons. Since the action is taking place on the night side of the Earth, there are no photoelectrons to help carry off the charge and the Orbiter is dependent solely on ram ions for its neutralization. Suppose the ram ion current is sufficient to neutralize the Orbiter; however, the free flying object is positioned in the wake of the Orbiter, and no ram ion current can reach him. Since the velocity of the precipitating electrons (about 4 keV) is 30,000 km/sec, the electrons can easily penetrate into the wake and can land on the object.

What follows can be described in terms of two extremes:

1. As the object begins to charge up negatively due to the precipitating electrons, an electric field is built up around it which attracts positive ions and a positive plasma current flows across the wake and neutralizes the charged object. In this case there is no problem.

2. The object charges up to 5,000 V because the combination of the electric field configuration and the ion trajectories do not allow the ions to reach the object. Now, if the object comes into contact with any part of the vehicle or the payload, a discharge will be produced which is similar to those that caused many problems in the geostationary earth orbit.

Since plasma behavior is in general quite complex, conceivably a situation may arise which is between the two extremes described above, or for that matter unanticipated effects could also be produced.

OBJECTIVES

We propose an experiment to study the electrical properties of the Orbiter wake region, the objective of which is to determine what plasma effects do actually occur in this region, and how significant they might be relative to EVA or satellite deployment in the Orbiter wake when the vehicle is in polar or near-polar orbits.

EXPERIMENT PLAN/DESCRIPTION

The experiment consists of an instrumented sub-satellite which serves as the "small body" and which is attached by means of a long umbilical to the Shuttle Orbiter. This umbilical also serves structurally as a tether to limit the distance at which the ss will be deployed.

The minimum experimental configuration for the sub-satellite would consist of a 30-50 cm diameter gold-plated sphere attached to the Orbiter payload bay by a 20-40 meter long insulated wire. The sphere would carry a light to determine its location in shadow and night, using the Orbiter television cameras. Voltage on the sphere would be varied from low to high voltages and the return current to the Orbiter measured. This would be the primary experimental data, and would allow prediction of wake effects in polar orbits. The sphere could also carry a variety of plasma diagnostic instruments. However, initial experiments will use only the basic sphere, with instruments added only in later flights, as required. The wake region will be mapped by putting the Orbiter in a slow roll (1 rpm) around an axis perpendicular to the velocity vector. The centrifugal force will then keep the sphere at the end of the extended umbilical, which will act as a tether and the sphere will pass in and out of the wake of the Shuttle. When the experiment is completed, the umbilical will be cut inside the payload bay, and the sphere jettisoned to space; in order to avoid the complexity and cost of a mechanism to pull the sphere back inside the payload bay.

Experiment Parameters

ss: size: .125 m^3
weight: 10 kg
power: 50 W

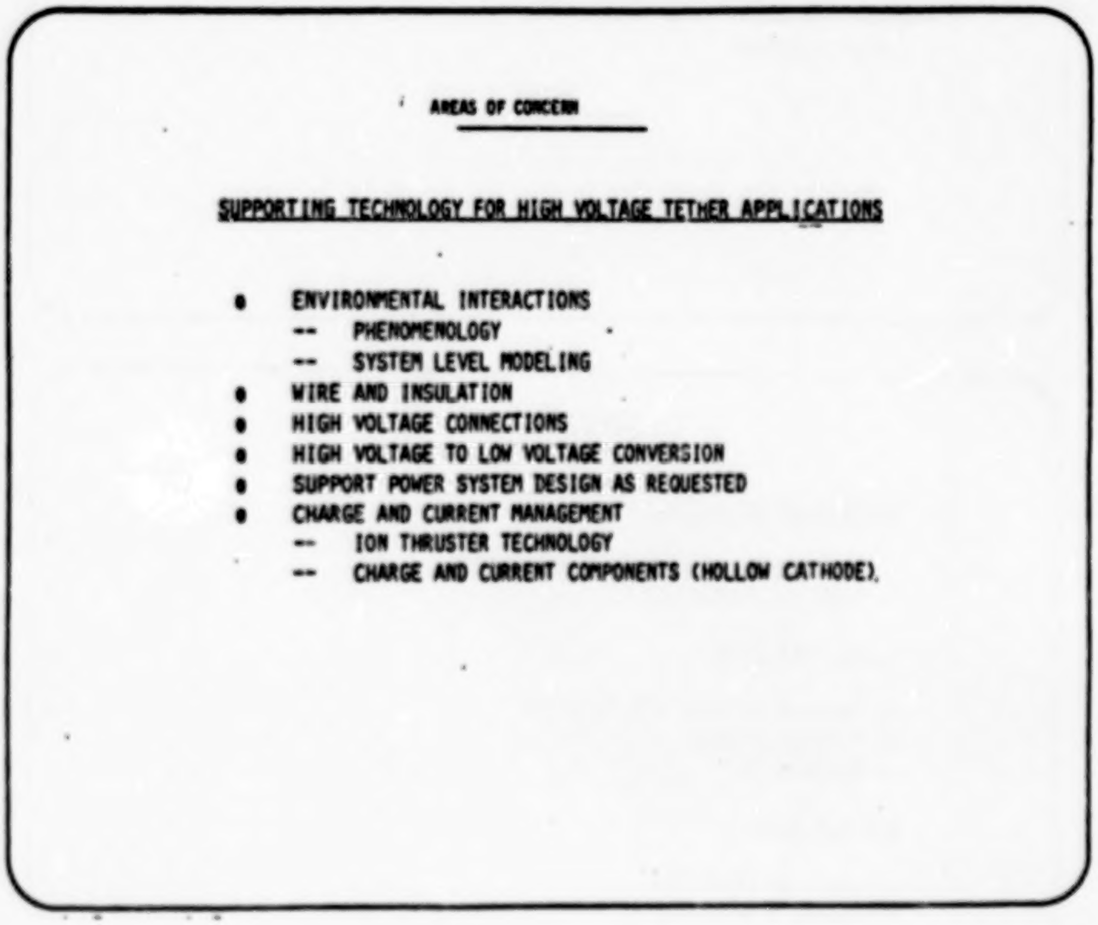
Payload bay instrumentation and umbilical deployment mechanism:
Size: .25 m^3
Weight: 100 kg
Power: 50 W

Orbit: Any inclination, preferably with maximum eccentricity to sample different altitudes. Must have day and night side passes.

Cost: $250 K for basic sphere and deployment mechanism. Integration, data acquisition not included.

Schedule: Available for flight 2 years after start (possibly sooner).

APPLICATION NO. 5 - DAVID D. RENZ, Lewis Research Center
SPACE POWER TECHNOLOGY



AREAS OF CONCERN

SUPPORTING TECHNOLOGY FOR HIGH VOLTAGE TETHER APPLICATIONS

- ENVIRONMENTAL INTERACTIONS
  - PHENOMENOLOGY
  - SYSTEM LEVEL MODELING
- WIRE AND INSULATION
- HIGH VOLTAGE CONNECTIONS
- HIGH VOLTAGE TO LOW VOLTAGE CONVERSION
- SUPPORT POWER SYSTEM DESIGN AS REQUESTED
- CHARGE AND CURRENT MANAGEMENT
  - ION THRUSTER TECHNOLOGY
  - CHARGE AND CURRENT COMPONENTS (HOLLOW CATHODE).

TETHER WIRE AND INSULATION TECHNOLOGY FOR HIGH VOLTAGE APPLICATIONS

ENVIRONMENTAL INTERACTIONS CONCERNS

-- INSULATION MUST STAND OFF FULL VOLTAGE

-- PINHOLES IN INSULATION MAY CAUSE EXCESSING CURRENT LEAKAGE (POSITIVE CONDUCTOR VOLTAGES)

-- POSSIBLE ARCING NEAR PINHOLES, METAL-INSULATOR BOUNDARIES (NEGATIVE CONDUCTOR VOLTAGES)

MATERIAL CONCERNS

-- DEGRADATION OF INSULATION UNDER ORBITAL OXYGEN FLUXES

-- STRENGTH/WEIGHT OF WIRE + INSULATOR

- INTERCALATED GRAPHITE CONDUCTOR?

TECHNOLOGY FOR HIGH VOLTAGE CONNECTIONS

-- SIMILAR CONCERNS

ENVIRONMENTAL INTERACTIONS FOR HIGH VOLTAGE TETHER SYSTEMS

SYSTEM FLOATING VOLTAGES

-- INSULATORS & CONDUCTORS IN PLASMA/BEAM

-- START UP & STEADY STATE

TETHER INSULATION

-- SUSTAINS VOLTAGE DROP TO PLASMA

-- PINHOLE LEAKAGE

-- DEGRADATION

ELECTRON BEAM

-- START UP TRANSIENTS

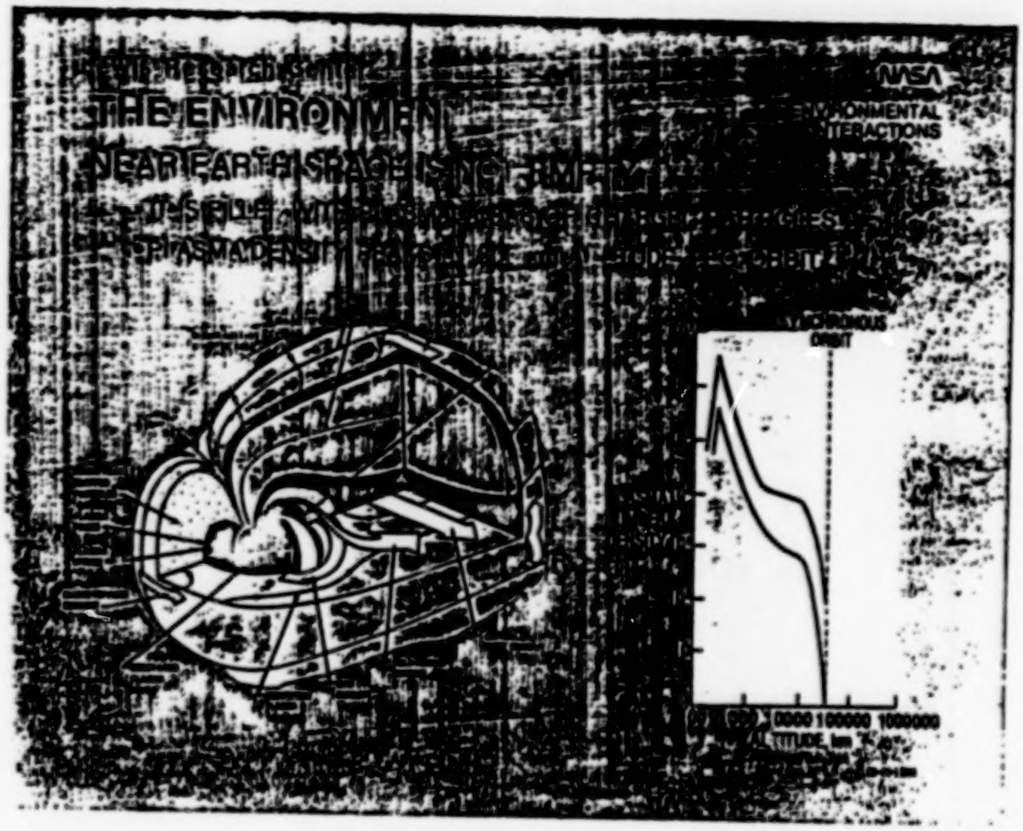
-- ESCAPE FROM SHUTTLE

- POTENTIAL BARRIERS, LOCAL SURFACE POTENTIALS
- SPACE CHARGE
- MAGNETIC FIELD EFFECTS
- PLASMA HEATING, ETC.

RELATED ENVIRONMENT QUESTIONS

-- I-V CURVE FOR SPHERE

-- PERSISTENCCE OF ALFVEN WINGS OR OTHER PLASMA DISTURBANCES



Lewis Research Center

NASA

ENVIRONMENTAL INTERACTIONS

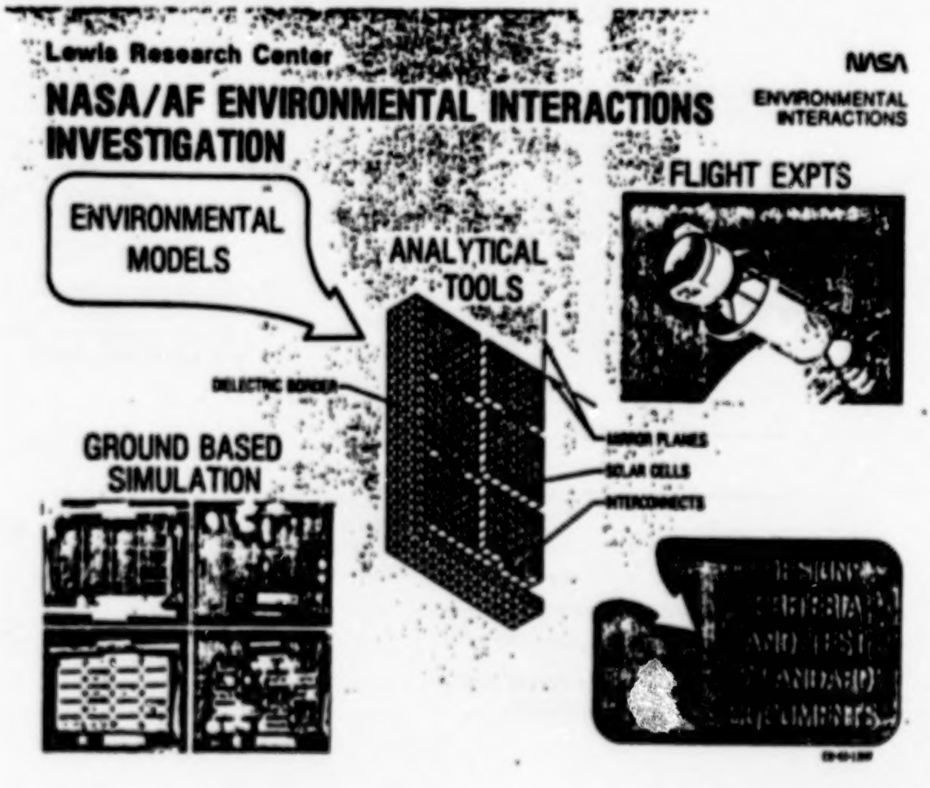
THE ENVIRONMENT

NEAR EARTH SPACE IS NOT EMPTY

- IT IS FILLED WITH PLASMA [illegible] OF CHARGED PARTICLES
- PLASMA DENSITY [illegible] ALTITUDE [illegible] ORBIT

SYNCHRONOUS ORBIT
100000
1000000
ALTITUDE, km

ORIGINAL PAGE IS
OF POOR QUALITY



Lewis Research Center

NASA

ENVIRONMENTAL INTERACTIONS

NASA/AF ENVIRONMENTAL INTERACTIONS INVESTIGATION

ENVIRONMENTAL MODELS

ANALYTICAL TOOLS

FLIGHT EXPTS

GROUND BASED SIMULATION

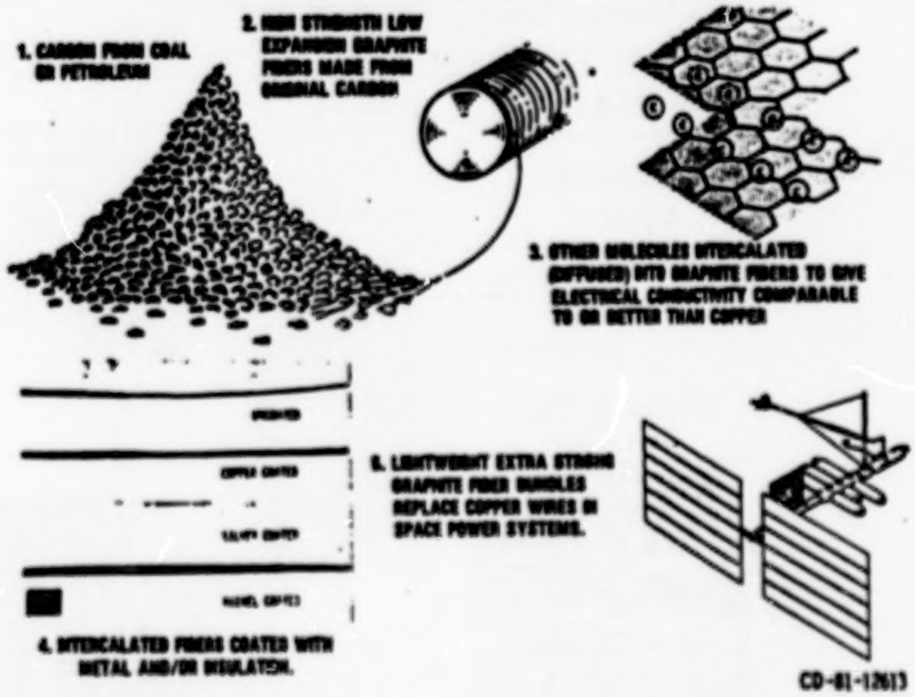
DESIGN CRITERIA AND TEST STANDARDS DOCUMENTS

DIELECTRIC BORDER
MIRROR PLANES
SOLAR CELLS
INTERCONNECTS

CONVERSION OF HIGH VOLTAGE TETHER POWER TO DISTRIBUTION VOLTAGES

- 10-15 KV DEVICE TECHNOLOGY
  - -- NEW DOUBLE DOPED SILICON SWITCH
    - + NOW UNDER EARLY DEVELOPMENT
    - + CAPABLE THEORETICALLY OF UP TO 20,000 VOLTS IN A SINGLE DEVICE
  - -- MANY TRANSISTORS OR SCR'S IN SERIES
  - -- VACUUM TUBES
- CIRCUIT DEVELOPMENT
- ENVIRONMENTAL TESTING
- FLIGHT TEST

GRAPHITE INTERCALATED CONDUCTOR


1. CARBON FROM COAL OR PETROLEUM
2. HIGH STRENGTH LOW EXPANSION GRAPHITE FIBERS MADE FROM ORIGINAL CARBON
3. OTHER MOLECULES INTERCALATED (DIFFUSED) INTO GRAPHITE FIBERS TO GIVE ELECTRICAL CONDUCTIVITY COMPARABLE TO OR BETTER THAN COPPER
UNCOATED
COPPER COATED
SILVER COATED
NICKEL COATED
4. INTERCALATED FIBERS COATED WITH METAL AND/OR INSULATION.
5. LIGHTWEIGHT EXTRA STRONG GRAPHITE FIBER BUNDLES REPLACE COPPER WIRES IN SPACE POWER SYSTEMS.

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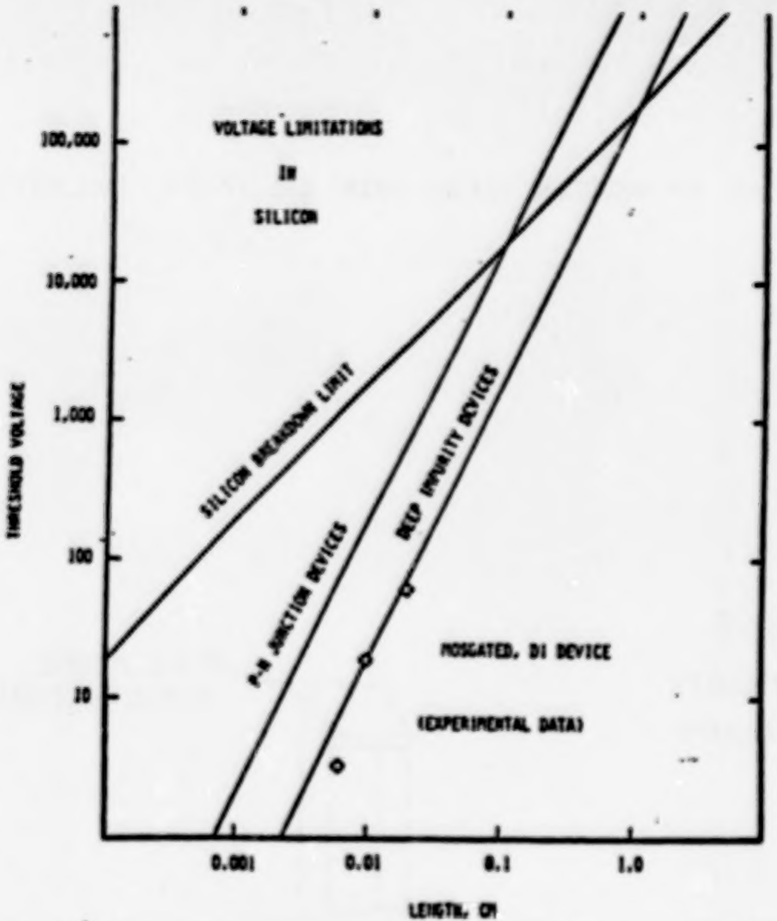


LERC CAPABILITIES

POWER MANAGEMENT AND DISTRIBUTION BRANCH
- MATERIALS DEVELOPMENT
- DEVICE DEVELOPMENT
- ENVIRONMENTAL INTERACTION

BRANCH LEVEL ACTIVITY -- 10 YEARS

ELECTRIC PROPULSION BRANCH
- ELECTRIC PROPULSION TECHNOLOGY
- ADVANCED PROPULSION RESEARCH

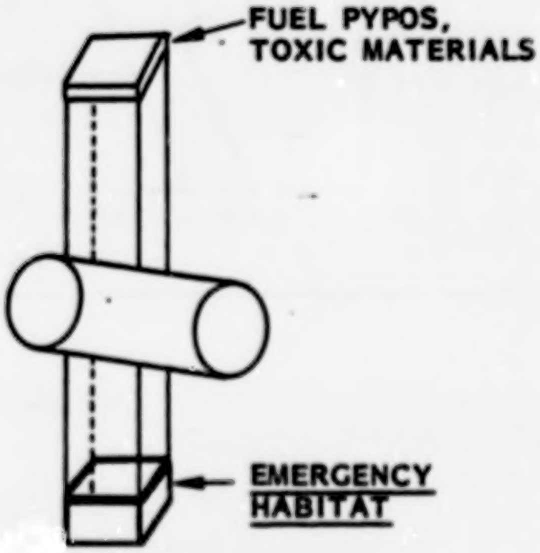
SPACE EXPERIMENTS BRANCH
- ION AUXILIARY PROPULSION (IAPS)

BRANCH LEVEL ACTIVITY - 20 YEARS

APPLICATION NO. 6 - WORKSHOP SAFING USING THE TETHER, JACK PRICE

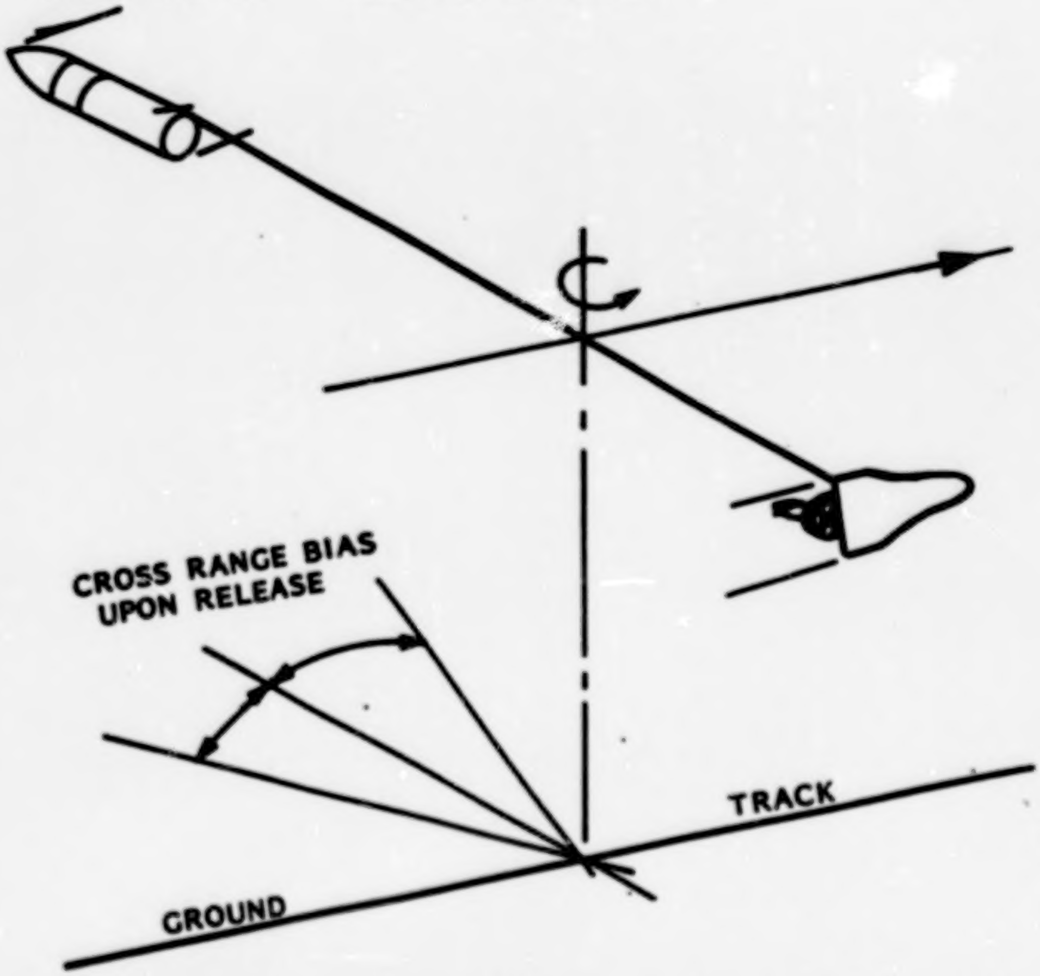
EARTH PRECIPENCE

- REVETMENTS
- FUEL DUMPS


FUEL PYPOS,
TOXIC MATERIALS
EMERGENCY
HABITAT

ARTIC
EMERGENCY
SHELTERS

APPLICATION NO. 7 - DEAN MONITOR, MARTIN



TESTS: UTILIZING GEMINI DEPLOYMENT AND STATIONKEEPING TECHNIQUES

- ARTIFICIAL "G" (0.001-0.1) WITHIN SPACELAB/ORBITER
  - CHECKOUT EQUIPMENT, PROCESSES, PROCEDURES PRIOR TO COMMITMENT TO A PERMANENT SPACE STATION
- PROPELLANT RECOVERY OPERATIONS DEVELOPMENT
- HUMAN FACTORS ADAPTATION STUDIES
- TETHER RELEASE
  - ESTABLISH THE VERTICAL SPIN/SWING PLANE ANGLE FOR CROSS-RANGE TRAJECTORY
  - ESTABLISH SPIN/SWING VELOCITY AND TIMING FOR ORBITAL TRANSFER

IV. ADDITIONAL PRESENTATIONS MADE TO THE PANEL

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N85-20374

PRESENTATION 1 30/9/82

TITLE: STUDY PROPOSAL FOR THE POSSIBLE USE OF TSS AS AN AERODYNAMIC FACILITY FOR AEROSPACE APPLICATIONS

Carlo BUONGIORNO, Professor, University of Rome, Italy

1. INTRODUCTION

The design of a cost-effective Orbital Transfer Vehicle (OTV), to be employed in conjunction with the envisaged Space Station System (SSS), is strongly related to the possibility to retrieve it, in the most economical way from the final orbit back to the SSS departure orbit. A typical mission is the injection of a spacecraft in a GTO orbit employing an OTV, and then after the spacecraft apogee injection to retrieve the OTV back to the SSS. From some preliminary analysis it appears that by using some retrofiring at the apogee and by airbraking the OTV at the perigee in the upper layers of the Earth atmosphere, it is possible to circularize, in an economic way the initial high elliptic orbit, in order to perform the correct rendezvous with the SSS.

The feasibility of such system is strongly linked to the trade-off analysis on the following main parameters:

i) Complications induced by the airbraking maneuvering system versus a conventional circularization and rendezvous performed by the retrofiring of the OTV main engine

ii) Heat Shield mass and heat shield and air brake configuration versus propellant masses needed for a conventional maneuver.

Regarding the point i) and ii) the most stringest requirement is the knowledge of the aerodynamic coefficients and of the heat fluxes entering into the heat shield at the gasdynamic regimes encountered by the OTV during the flight through the EARTH atmosphere layers ranging from 200 km and 80 km, which means a variation of the free stream parameters of the following order of magnitude:

At 200 km

$$K_{n_\infty} = 54 \qquad S_\infty = \frac{V}{\bar{V}} \cong 10$$

At 80 km

$$K_{n_\infty} = 0.001 \qquad Re = 60 \cdot 10^3 \quad M_\infty = 37$$

based on OTV body diameter (≃ 4 m) and physical parameters of Earth atmosphere by U.S. Standard Atmosphere 1976.

The Kn_∞ is the knudsen number given by the ratio between molecular mean free path and a body length S is the speed ratio V_∞/V, between OTV flight velocity at perigee and V is the mean molecular velocity M_∞ is the free stream Mach Number. Re_∞ is the free stream Reynolds number.

The inspection of the range of variation of the gasdynamic numbers shows that OTV during the airbraking experiences all the transitional flow regimes going from free-molecular to the continuum flow.

The transition regimes have been the object of extensive studies in the past twenty years both theoretical and experimental; the attempt of covering the entire regime with an unique treatment have been particularly successful making recourse to semiempirical corrleations that far from respecting complete generality are at the present time the only and uncertain informations for engineering purposes. On theoretical ground the investigators mostly dealt with postulated ideal model appropriate for limited ranges of flow parameters and the results are minly qualitative.

The most accepted classifications of the transition regimes distinguishes the following stages

a) Near free molecular regime
b) Higher order collisions non-continuum regime
c) Fully merged layer almost continuum regime
d) Incipient merged layer regime
e) Fully viscous layer regime
f) Interaction regime

The parameters that characterize the various regimes are as previously specified the Kn_∞, M_∞, Re_∞ and T_b/T_∞, where T_∞ is the free stream molecular temperature and T_b is the body surface temperature.

In view of these preliminary considerations it appears that the trade-off analysis for the point i) and ii) can be made only if we know the accuracy with we can determine the aerodynamic coefficients in the transitional flow regimes. Because of the inherent difficulties relate to the duplication of the abovesaid transitional flow regime in a ground based aerodynamic facility, it is practically impossible to design and to construct such facility from the point of view of the engineering problems, of the state of the art of the specific technologies and for the consequent development costs.

The proposed solution to such intriguing problem is the exploitation of the Tether Satellite System (TSS). On a first instance, the TSS appears to be very appealing tool for this kind of gasdynamic research, by employing it as a spaceborne variable low density wind tunnel.

The downward deployment, by using the TSS, of a body configuration of a given external shape from the STS orbital height (≃ 200 km) up to 90 ÷ 100 km can make possible the performing of the measurements of the aerodynamic coefficients and of the heat fluxes in a continuous way and for the needed testing time, throughout all the transitional regimes to be encountered by OTV during its airbraking maneuver.

2. THE PROPOSED FACILITY

The generic component of the aerodynamic force can be expressed as:

$$F_A = \frac{1}{2} \rho_\infty V_\infty^2 A c_A$$

ρ_∞ = density of the medium

V_∞ = flight velocity

A = body reference area (e.g., cross section area)

c_A = aerodynamic coefficient.

The aerodynamic coefficient c_A is, generally, a function of the speed ratio S, of the medium composition, and of the physical characteristics of the surface of the body. Therefore, the determination of c_A is made through the measurement of F_A, and the exact knowledge of ρ_∞, V_∞ and A. In view of these considerations, the TSS concept can be exploited as an "in situ" wind tunnel and the propoved facility can be summarized as it follows:

(a) The system is consisting of the TSS and of the model to be tested.

(b) By means of some hundred meters of tether, the model is deployed from the TSS satellite, acting as a subsatellite (Fig. 1).

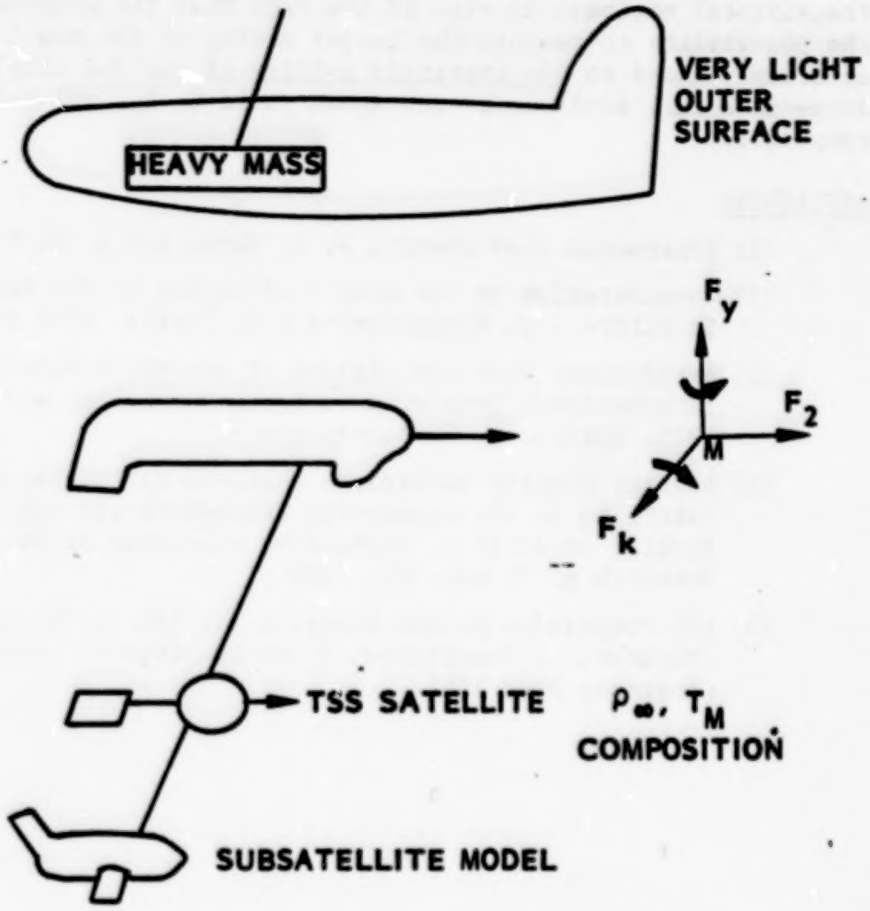
(c) The measurement of the force F_A acting on the subsatellite model is performed in the following way. The model is made in two parts: an inner heavy part where the majority of the mass is concentrated--connected through the tether to the TSS satellite (Fig. 2); an outer light part coinciding with the external model surface linked to the inner part through an elastic measuring system.

(d) Due to the high ratio between the mass of the inner and outer part, the elastic linking elements deformations will be function only of the forces acting on the external light part. Therefore, by measuring such deformations the three components of the total aerodynamic force and moment can be determined.

(e) The physical characteristics of the medium (ρ_∞, molecular composition; kinetic temperature, T_∞) are continuously measured by the atmospheric instrumentation available in TSS satellite.

(f) The external surface of the model is made with the same of material employed in the prototype.

(g) The velocity, V_∞, and the altitude of the TSS satellite can be determined very accurately with the standard system provided in the TSS.


VERY LIGHT OUTER SURFACE
HEAVY MASS
F_y
F_2
M
F_k
TSS SATELLITE
ρ_∞, T_M
COMPOSITION
SUBSATELLITE MODEL

$$F_A = \frac{1}{2} \rho V_\infty C_A A$$

$$C_A \cong C_A[P_\infty, \rho_\infty, T_\infty, \text{GAS COMPOSITION, SURFACE}]$$

$$C_A = \frac{2 F_A}{\rho_\infty V_\infty A}$$

Figure 1

C-4

3. CONCLUSIONS

In conclusion, the proposed use of TSS as an "in situ" low density wind tunnel can provide the most reliable data on the aerodynamics of the transitional regimes, in view of the fact that the proposed system gives the possibility to measure the forces acting on the model with a good accuracy jointed to the intrinsic ability of the TSS satellite to reproduce--in a full scale mode--the speed ratio S, ρ_∞, and the molecular composition.

4. REFERENCES

(1) Hypersonic flow theory, W. D. Hayes and R. F. Probstein.

(2) Consideration on the drag coefficient of the San Marco Satellite - C. Buongiorno and M. Trella, ATTI CRA n° 5 1964.

(3) Aerodynamic Drag Coefficient of San Marco Satellite - XI International Symposium on Space Technology and Science, 1975, Tokoyo, By C. Buongiorno.

(4) Diurnal Density Variations Measured by the San Marco III Satellite in the equatorial atmosphere (in coll. with L. Broglio et alii) C. Buongiorno - Journal of Geophysics Research n° 7, Vol. 81, 1976.

(5) MPD Propulsion system analysis for LEO to GEO Low-Thrust Transfer, C. Buongiorno, M. Di Giacinto - AIDAA, VI Congress, Rome 1981.

PRESENTATION 2

N85-20375

TRANSPORT PROCESSES IN THE UPPER ATMOSPHERE

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1 - Introduction

The unique capability of TSS to deliver and maintain payloads to altitudes below that of the Orbiter and to run tests over a relatively long period of time makes the system itself very attractive to study thermo-fluid-dynamic processes in the upper atmosphere. Use of TSS will allow, in fact, to carry out fundamental studies within the field of energy, mass and momentum transfer between a flying body and a very peculiar medium. This medium and its particular features cannot be easily reproduced in laboratory test rigs even in its simpler thermodynamic states. TSS gives the opportunity, instead, to perform measurements even in much more complex states such as those encountered in the lower thermosphere where strong coupling phenomena between the ionosphere and the atmosphere are present. Therefore TSS can be regarded as an "open continuous wind tunnel" where the flowing medium can be varied by varying the altitude of the tethered satellite (TS) which has the "tether" advantage over the free flying satellites. In a typical downward mission the molecular mean free path of atmosphere around the satellite will vary from hundreds of meters at Orbiter level to few centimeters at the lowest altitude. Strong variations are also encountered for the temperature, pressure, density and molecular weight.

2 - Outline of the research

The present research intends to exploit TSS as an open continuous wind tunnel to experimentally investigate aerodynamic and heat transfer processes within the flow range encountered by TS in downward missions. In such missions, because of the large Knudsen number variation, it will be possible to perform thermo-fluid-dynamic tests in the free molecule flow regime and in the near free molecule and low density transitional flow regimes. In the free molecule regime it will be important to measure simultaneously both fluid dynamic parameters and temperature distribution on body surface since aerodynamic forces depend on this latter. With regard to transitional flow regimes more experimental data are needed in order to better establish aerodynamic and heat transfer coefficients correlations.

The experimental tests which can be performed with a tether facility may be roughly divided into the following three groups:

a) Tests on the satellite itself without undergoing substantial modification of its design; they can be run by properly instrumenting the satellite surface and the tether and are aimed at obtaining fundamental data on the transitional flow regimes for TS geometry as well as to improve the satellite operation and design.
b) Tests which consider an adequate implementation of the satellite design consisting of models carried aboard; these are tests on basic geometries such as linear or blunt bodies which should be exposed to the free stream.
c) A peculiar class of tests could be performed by designing a new tethered satellite mainly devoted to energy, mass and momentum transfer studies on particular geometries.

All these groups of tests look quite interesting in terms of the answers they can give to operation and development of the satellite and to questions regarding transport processes in the upper atmosphere. For all of them preliminary, ground based, researches must define subsystems configuration, including nature of exchange surfaces, and the experimental tecniques to be employed. Furthermore, the quality and the specifications of the instrumentation necessary to perform space tests and to characterize the free stream must be determined. Finally, expecially with regard to the last two groups of tests, it has to be analized the problem of the stability of satellite attitude with respect to free stream and of its control.

3 - Objectives of the research

The primary objective of the proposed study is to measure aerodynamic and heat transfer coefficients within the thermo-fluid-dynamic range experienced by the satellite and to compare them with previous correlations. This will allow to have a deeper insight in flows whose characteristic are difficult to reproduce with ground tests and, in particular, in the above mentioned transitional flow regimes.

Besides the answers and checks they will give on fundamental data on aerodynamic and energy tranfer coefficients, the proposed tests are preliminary to assess the feasibility of a number of applications such as development of the tethered satellite itself, free flying satellites lifetime prediction and

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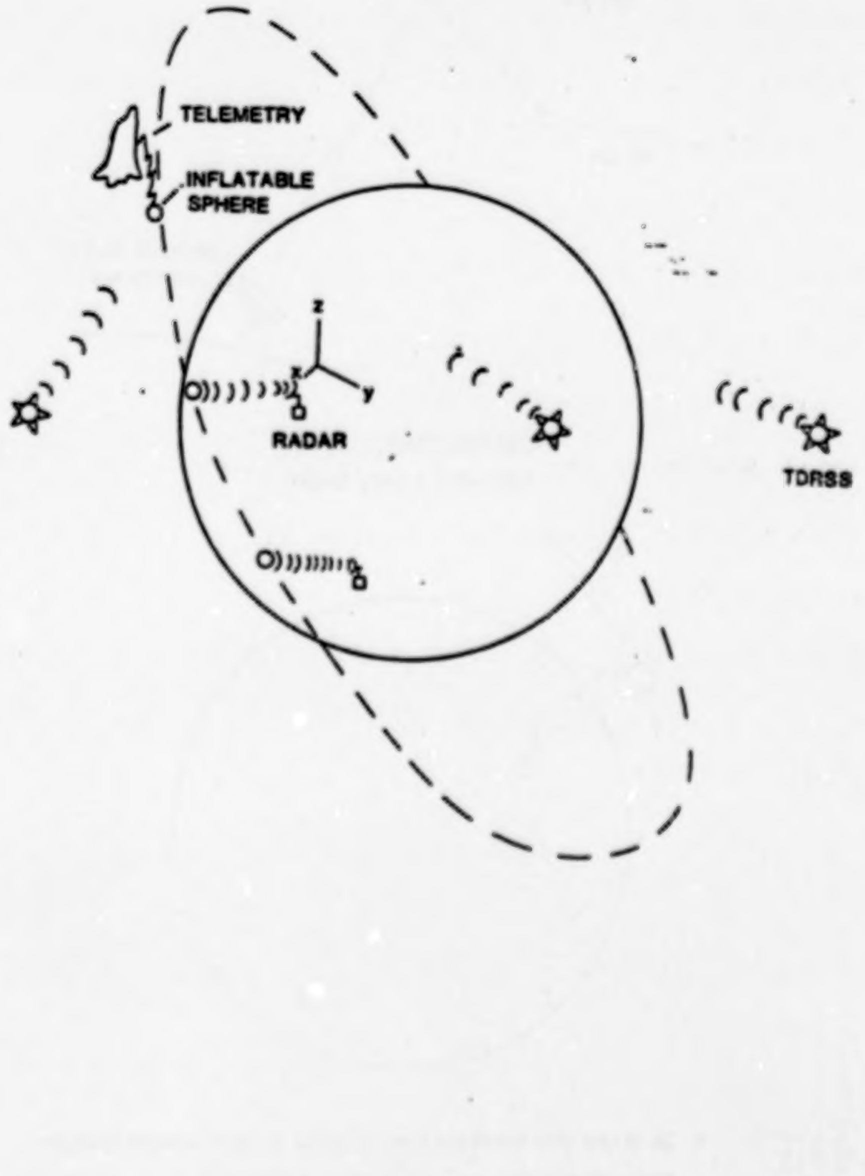
airbraking of Orbital Tranfer Vehicles (OTV). With regard to TS development, it has been pointed out that its operation at altitudes below 125 km could be very crucial due to aerodynamic heating and stability problems; it is necessary therefore to measure with sufficient accuracy energy and momentum inputs within this altitude range. The long time range prediction of the orbit, and therefore of the lifetime, of a free flying satellite relies on a better knowledge of the interaction between satellite and free stream i.e. a more accurate determination of drag, lift and torque and of the atmospheric density distribution. The airbraking at the perigee, combined with some retrofiring at the apogee, looks quite promising to perform an economical rendez-vous of OTV's with space stations; also in this case it is auspicable to know with major confidence aerodynamic and heat transfer coefficients so to properly design air brakes and heat shields configuration.

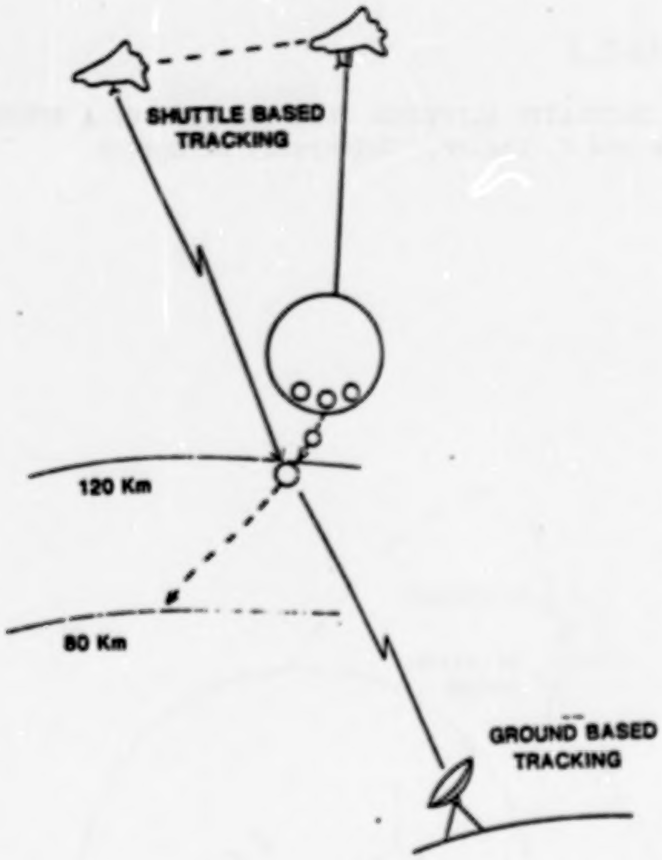
It is therefore believed that a definite need exists to better investigate transport processes in the upper atmosphere and the Tethered Satellite System gives to the scientific community the opportunity to perform these studies.

PRESENTATION 3

DENSITY AT SATELLITE ALTITUDES FROM THE DRAG OF A SPHERE

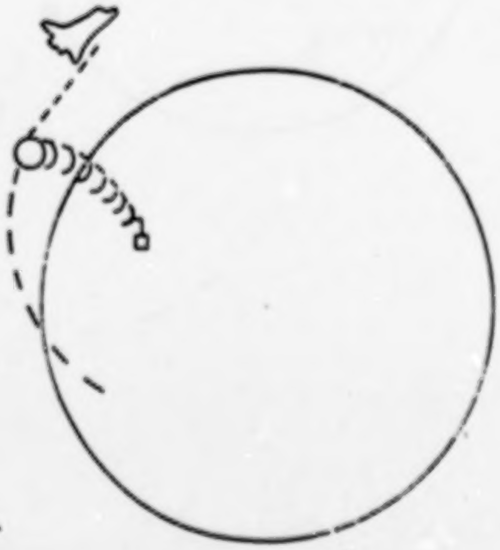
J. Luers and N. Engler, University of Dayton


TELEMETRY
INFLATABLE SPHERE
z
x
y
RADAR
TDRSS


SHUTTLE BASED TRACKING
120 Km
80 Km
GROUND BASED TRACKING

PREVIOUS FEASABILITY STUDY

SURVIVABLE REENTRY SPHERE



- CALCULATED SKIN TEMPERATURE VS. ALTITUDE BY HEAT TRANSFER EQUATIONS
- DETERMINED NECESSARY REVERSE EJECTION SPHERE VELOCITY TO PREVENT BURNUP

- DETERMINATION OF SPHERE SKIN TEMPERATURE

  APPROACH: HEAT TRANSFER ANALYSIS

- DETERMINATION OF AMBIENT TEMPERATURE

  APPROACH: LITERATURE REVIEW

- SPHERICITY NECESSARY

  APPROACH: LITERATURE REVIEW OF ROUGHNESS EFFECTS IN FREE MOLECULAR FLOW

- SPHERE SURVIVABILITY

  APPROACH: LEAKAGE PROBLEM OF INFLATABLE SPHERE (INFO AVAILABLE)

  MYLAR PROPERTIES AT COLD/HOT TEMPERATURES (INFO AVAILABLE)

- ALTITUDE OF SPHERE BURNUP

  APPROACH: HEAT TRANSFER ANALYSIS (SOFTWARE ALREADY DEVELOPED)

- ELLIPTICAL VS. SPHERICAL ORBITS

  APPROACH: TRADEOFF ANALYSIS BETWEEN DESIGN REQUIREMENTS AND TRACKING ACCURACIES

TECHNIQUE

IN EARTH FIXED COORDINATE SYSTEM

$$M\ddot{Z} = 1/2\rho C_D A V^2 + mg_z + C_z$$

$$M\ddot{Y} = 1/2\rho C_D A V^2 + mg_y + C_y$$

$$M\ddot{X} = 1/2\rho C_D A V^2 + mg_x + C_x$$

WHERE:

M = MASS OF SPHERE

A = SPHERE CROSS SECTION

$C_{x,y,z,}$ = CORIOLIS COMPONENTS

V = SPHERE VELOCITY RELATIVE TO AIR = f (WIND)

ρ = ATMOSPHERIC DENSITY

C_D = SPHERE DRAG COEFFICIENT

$g_{x,y,z}$ = GRAVITATIONAL COMPONENTS

KNOWN:

$m, x, y, z, C_D, g_{x,y,z}, C_{x,y,z}, W_z$

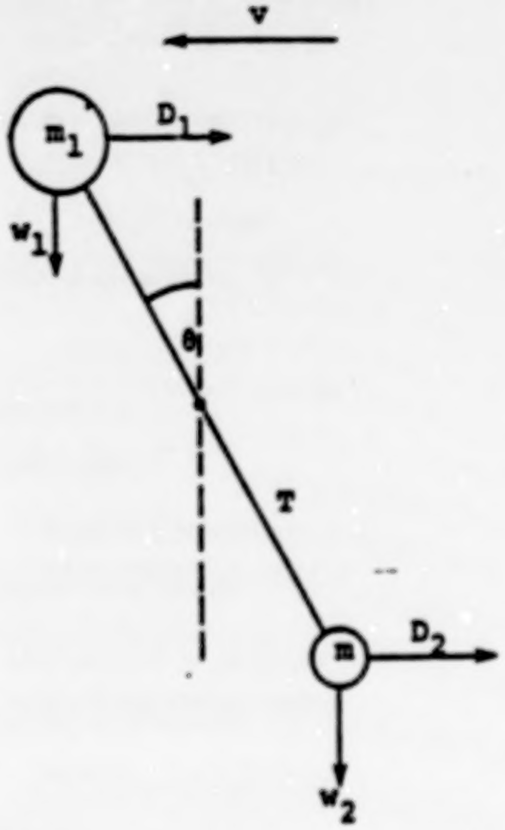
SOLVE FOR:

ρ, W_x, W_y

PRESENTATION 4

TENSION MEASUREMENT OF DENSITY

N. Engler, University of Dayton



Horizontal

$$D_1 - T \sin\theta = m_1 r_1 \dot{\omega}$$

$$D_2 + T \sin\theta = m_2 r_2 \dot{\omega}$$

Vertical

$$T \cos\theta + \frac{K m_1}{r_1^2} = m_1 r_1 \omega^2$$

$$-T \cos\theta + \frac{K m_2}{r_2^2} = m_2 r_2 \omega^2$$

where

$$K = G M_e$$

$$D = \tfrac{1}{2} \rho C_D A V^2$$

From the equation on slide one, one can get,

$$\tan\theta = \frac{\left(\frac{C_D A_2 \rho_2 r_2}{m_2} - \frac{C_D A_1 \rho_1 r_1}{m_1}\right)\left(m_1 r_2^1 + m_2 r_1^2\right)}{2\left(r_1^3 - r_2^3\right)\left(\frac{m_1}{r_2} + \frac{m_2}{r_1}\right)} \qquad (5)$$

If we assume that

$$\rho_1 << \rho_2 \quad \text{and} \quad r_1 = r_2$$

Then

$$\tan\theta = \frac{C_{D_2} A_2 \rho_2 r_2^4}{2m_2(r_1^3 - r_2^3)} \qquad (6)$$

Now the problem is in assigning an altitude for determining ρ_2.

If a flat earth is assumed

$$z_2 = z_1 - \ell \cos\theta \qquad (7)$$

or

$$r_2 = r_1 - \ell \cos\theta$$

and equation 6 becomes

$$\sin\theta = \frac{C_D A_2 \rho_2 r_2^2}{6 m_2 \ell} \qquad (8)$$

where all second order terms in the expansion of $r_1^3 - r_2^3$ have been ignored.

Procedure

Choose an ℓ and z_1

Assume $\theta = 0$

Use equation 7 for z_2 and hence ρ_2

Put value of ρ_2 back in (8) to find θ.
Continue until it converges.

N85-20376

PRESENTATION 5

THE SATELLITE SAIL

Jerome Pearson*
Air Force Wright Aeronautical Laboratories
Wright-Patterson AFB, Ohio

Abstract

It is proposed to suspend an airfoil from the Space Shuttle by a long tether into the upper atmosphere to provide a horizontal force on the Shuttle, thereby changing its orbital plane most efficiently. The airfoil would need high-temperature skin and tether, and remotely controlled flaps to adjust its angle of attack. The airfoil could also be used as a hypersonic facility to measure aerodynamic characteristics at extreme altitudes and velocities. This use would require a vertical lift force to counteract the drag force and prevent the Shuttle orbit from decaying too rapidly during the aerodynamic measurements.

I. Introduction

Since the first earth satellite was orbited in 1957, there has been an increasing use of many different kinds of satellites in earth orbit to perform a variety of tasks. For some of these tasks, such as worldwide communications, the satellite must be in an equatorial orbit with a period of one day, so as to appear fixed over a point on the equator. For other tasks, it is desirable to have the satellite in polar orbit, so as to pass over every part of the earth. For manned satellites and other uses, orbits of intermediate inclination to the equator are desired. For example, the orbit that requires minimum fuel to reach from a given launch point has an inclination equal to the latitude of the launch point. As a result, there are hundreds of satellites now in earth orbit, with inclinations to the equator ranging from zero to more than 90 degrees (retrograde).

With the advent of the re-usable Space Shuttle, it has become possible for one spacecraft to launch or retrieve many satellites on a single mission. This means that the shuttle must change its orbital inclination before each deployment or retrieval of a satellite, in order to match the satellite orbit. Unfortunately, changing the inclination of a spacecraft orbit is very expensive in energy. For example, the total velocity change required to launch a satellite into a minimum-energy orbit from Cape Canaveral is about 8 kilometers per second. For a polar orbit, the requirement is about 9 kilometers per second, because the additional velocity of the earth's rotation cannot be used.

However, to change the spacecraft orbital inclination from equatorial to polar once it is in orbit requires a total velocity change of 12 kilometers per second. This is such a severe requirement that it is easier to land and start all over again rather than change the velocity while the spacecraft is in orbit. Smaller orbital inclination changes can be done using much less velocity change, but it is still a very difficult operation with current rockets. No spacecraft has yet changed its orbital inclination by more than one or two degrees.

II. Shuttle Sail Concept

The purpose of this paper is to propose a new technique for satellite plane changing that is more efficient than rocket thrust or aerodynamic maneuvering.[1] The satellite sail is an airfoil suspended into the upper atmosphere on a long tether, allowing it to experience significant aerodynamic forces while the satellite is above any sensible atmospheric drag. The airfoil is oriented so as to provide a horizontal lift force on the satellite, thereby processing its orbital plane to the desired new inclination. The device is called a satellite sail because it would function analogously to a sail on a watership; it would change the vessel's velocity by intercepting the relative wind.

An artist's concept of the satellite sail is shown in Figure 1. The satellite, shown here as the Space Shuttle, is in low orbit, about 200 km above the earth, and above the sensible atmosphere to the extent that aerodynamic drag is negligible. The airfoil is stored for launch in the Shuttle cargo bay and, once in orbit, is deployed downward from the satellite by the long tether and reel mechanism, and is stabilized by the gravity gradient. The Shuttle sail would be capable of multiple re-use; it is designed of high-temperature materials with no ablation during use. The tether itself could easily be replaced to prevent excessive abrasion by the reel mechanism.

Requirements

The Shuttle sail is dependent on two previous developments—the long-thethered satellite and the hypersonic airfoil. Plans have been developed by Colombo to tether subsatellites up to 110 km

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Engineering Technology Group
Associate Fellow AIAA

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N85-20376

below the Space Shuttle for scientific measurements at an otherwise inaccessible altitude.[2] These long-tethered satellites would be stabilized vertically by the gravity gradient.[3] It has also been proposed that satellites be attached to the earth and moon by even longer tethers.[4] The dynamics of the tether and satellite motions have been investigated and Rupp has patented a mechanism for deploying and retrieving such a tether.[5, 6, 7] The conclusions of these and other technical studies is that tethered satellites with tether lengths of tens or hundreds of kilometers can be successfully deployed, stabilized by the gravity gradient, and retrieved.

The shuttle sail concept also draws upon the high-temperature, hypersonic design experience growing out of the Space Shuttle program and of research on the "synergetic" maneuver. An aerodynamic vehicle such as the Space Shuttle can use the atmosphere to change its orbital plane. Using rocket thrust to lower its orbit, the Shuttle could dip into the atmosphere, bank to provide a horizontal lift force, then use rocket thrust again to raise its orbit back to the former value, in the new plane. This maneuver is called the "synergetic" plane change, and it was developed by the United States Air Force in the 1960's during the Dynasoar program by London, and later optimized.[8, 9] These Air Force studies also developed designs for high lift/drag hypersonic airfoils, and the National Aeronautics and Space Administration has developed high-temperature insulation for the surfaces of re-entry vehicles.[10, 11] Combining these technologies has resulted in proven design techniques for hypersonic, high-temperature wing design.

Baseline Design

We will now examine in detail one point design for the satellite sail. The Space Shuttle operational characteristics and plane-changing requirements indicate the use of a typical, symmetric, highly sweptback hypersonic airfoil with added shuttle-tile thermal protection.[12] The thickness-chord and edge radius-chord ratios can be minimized because there is no need for significant internal volume or great stiffness.

The baseline design, shown in Figure 2, is a 100-square-meter airfoil of bolted, two-section construction, hinged to fold into the Shuttle cargo bay. The overall length is 27 meters, the maximum width is 5 m, and the maximum thickness is 15 cm. The airfoil has a 10-degree half-angle nose and a rectangular aft section. The construction is typical graphite/epoxy composite structure with central spar, edge tubes, and integral stiffeners. The laminated graphite/epoxy skin is in typical 0/45/90 ply orientation for highest isotropic strength. The entire surface of the airfoil, including the control surfaces, is coated with 2 cm of Space Shuttle silica tile heat insulation, type LRSI.[11] The airfoil is symmetric and is equipped with moveable aerodynamic control surfaces (double-acting flaps that can be moved to either side of the airfoil), and a typical S-band radio receiver and controller to accept the commands from the satellite. The satellite sail would require a controlled angle of attack so that the horizontal force could be adjusted as a function of the satellite orbital position. The tether length and airfoil angle of attack, and thus the airfoil position and aerodynamic forces, can be controlled remotely from the satellite by the reel mechanism and by signals from a radio transmitter, or by a pre-programmed controller inside the airfoil. The total mass of the sail, including the controls, electronics, and motors, is estimated to be 1500 kilograms. This sail, lowered to 93 km altitude, will precess the Shuttle orbit by 1.5 degrees per day. The parameters are summarized in Table 1.

Simplified Analysis

When two masses in orbit are connected by a tether, the tether experiences a tensile force aligned along the local vertical. This is the gravity gradient force. When the Shuttle sail is deployed on its tether, the total force on the airfoil is composed of the gravity gradient, the aerodynamic lift and drag, and the tether tension. For a nominal Shuttle orbit of 185 kilometers altitude and a nominal sail altitude of 93 km, the gravity gradient produces a downward gravitational force on the sail of 0.04 g, or 592 newtons force for the baseline design.

Using Newtonian momentum theory, in which the airstream velocity component normal to the airfoil is reduced to zero upon impact with the airfoil, the lift coefficient is found to be 0.05961 for an angle of attack of 10 degrees. With a dynamic pressure Q of 54.4 newtons per square meter at 93-km altitude and an area A of 100 square meters, the total lift force (oriented laterally to the direction of the Shuttle motion) is 329 newtons.

At an angle of attack of 10 degrees, the L/D is typically a maximum of about 3.2, including the effects of skin friction and profile drag as well as the drag due to lift.[12] However, the tether drag must be taken into account. Assuming a tether diameter of 1.72 mm and an atmospheric Q that decreases by a factor of two for each 4 km of altitude, the additional drag of the tether reduces the effective L/D from 3.2 to 3.0. To minimize the reduction in L/D due to tether drag, it might be possible to elongate the tetherline itself in the direction of motion, using a flattened profile.

With L/D of 3, the drag force is 110 N, including the tether drag. The tether tension from these three mutually orthogonal components is then 686 N. With a safety factor of two, the baseline design can be met by a wire of A-286 high-strength, high-temperature steel alloy with a diameter of 1.72 mm. The upper part of the tether wire is under less severe temperature constraints and could use type 302 stainless steel with a diameter of 1 mm. Only the lowest 20 km of the tether would need the high-temperature steel.[13] Other superalloys or nonmetallic tethers might also be used.

The precession rate Ω is given in terms of the satellite angular velocity ω, the torque L acting on the satellite, and the moment of inertia I of the satellite in its orbit by the equation

$$\Omega = L/I\omega \qquad (1)$$

The torque L is the vector product of $r \cos\theta \times f$ where $r \cos\theta$ is the projected radius vector moment arm and f is the lateral force acting on the vehicle. Since $f(\theta)$ is given by $f \cos\theta$, the equation for the torque is

$$L = r\, f \cos^2\theta \tag{2}$$

The torque averaged over a half revolution is

$$L = r \cdot f \cdot \frac{2}{\pi} \int_{\theta=0}^{\pi/2} \cos^2\theta \, d\theta = \frac{rf}{2} \tag{3}$$

The equation for the precession rate is then

$$\Omega = \frac{L}{I\omega} = \frac{rf/2}{mr^2\omega} = \frac{f}{2mr\omega} \tag{4}$$

In order to precess the plane of the satellite orbit, the lift vector must be varied from port to starboard and back once per orbital revolution. Note that the required change in tether angle, and therefore the lift force and the flap setting, is very slow; a complete cycle from positive to negative tether angle takes more than an hour. This means that relatively slow, low-force flap actuators may be used. To increase the orbital inclination, the tether angle must provide a northward force as the satellite crosses the equator heading north and a southward force as the satellite crosses the equator heading south. Because the dynamic system has such a low inherent damping, the tether angle, and thus the lift force, will follow the flap control position very closely. The flap control signal is then the same as the required tether angle.

In Figure 3 is shown a schematic diagram of the geometry of the airfoil position as it varies from the starboard side of the Shuttle to the port side of the Shuttle and back again each orbit. Because of the changing angle of the tether (from 9 to 27 degrees, as shown in Table 2), the tether length λ must be varied cyclically over each orbit from 100.5 to 123.8 km to keep the sail at a constant altitude. With an orbital period of 88 minutes, the maximum tether length rate of change is 27.7 m/s. With a more powerful winch motor, higher rates of tether length change could be used to raise the airfoil to a higher altitude during the zero lift portion of its flight. This would reduce the drag and improve the overall efficiency. It would also allow additional cooling of the vehicle and tether, making possible higher Q operations with the same amount of thermal protection.

The change in tether length required for deployment, retrieval, and maintaining a constant sail altitude causes complex vibrations of the tether to be excited. These unwanted vibrations must be minimized in order to prevent errors in the controlled angle of attack of the deployed sail or large oscillations of the sail during retrieval. The dynamics of the tether with an end mass are discussed in more detail by Modi and Misra.[6]

The simplest control law, shown in Figure 4, is a sinusoidal input that causes the tether angle to peak just as the satellite crosses the equator. For a sail altitude of 93 km, an orbital period of 88 minutes, and a lift force of 329 N, the maximum lateral excursion of the sail on the end of the tether is 52 km, corresponding to a tether lateral angle of 29 degrees. The maximum lateral velocity is then 62 m/sec. This amounts to only a small perturbation on the nominal airspeed of 7 km/sec for the airfoil.

On the left side of Figure 5 is shown the dynamic pressure, Q, on the airfoil as a function of altitude.[14] For an airfoil area of 100 square meters, the precession rate of the space shuttle is shown on the right scale, using 70,000 and 100,000 kg as the mass of the shuttle in a 185-km orbit. The precession rate increases greatly as the airfoil is extended to lower altitudes, but the problems of aerodynamic heating are increased. The larger values of Q would require higher temperature materials for the leading edge of the airfoil, such as the HRSI silica tiles used on the Space Shuttle for temperatures up to 1500K. The precession rate could also be increased by simply increasing the area of the airfoil. Multiple-folding, deployable, or inflatable structures could be used for the larger areas and still fit within the Space Shuttle cargo bay.

III. Satellite Sail versus Synergetic Maneuver

In Figure 6 is shown a comparison of the velocity difference, in km/sec, required to change the orbital plane of the space shuttle various numbers of degrees, using rocket propulsion, using the optimum synergetic aerodynamic maneuver, and using the satellite sail with a lift/drag ratio of three.[5] In the all-propulsive maneuver, the satellite rockets are fired to provide a thrust at right angles to the current orbital velocity. The maneuver is quick, but very costly in fuel because of the high velocity change required. For low orbits, this is a very high velocity. The optimum synergetic maneuver requires that the shuttle fire rockets to dip into the upper atmosphere, then perform an aerodynamic maneuver to provide a side force, then fire rockets to return to the initial orbit. This maneuver is limited in efficiency by the lift-to-drag ratio of the Space Shuttle, which is not optimized for this function, and by the fact that the heavy Shuttle must first be lowered and then raised against gravity.

The use of the satellite sail is the slowest of the three maneuvers, but it is the most efficient. There is no need to de-orbit the shuttle into the upper atmosphere; the much lighter sail is lowered instead. The sail can be designed to provide optimum lift/drag for the chosen altitude. The aerodynamic lift provides the side force to change the orbital plane, and then the sail is raised back to the shuttle; rockets are used to make up for the energy lost to the drag of the sail and tether, which can be much less than that of the entire shuttle vehicle. There is no orbital velocity loss associated with lowering and raising the sail; the center of gravity of the satellite/sail system maintains a constant velocity in a fixed orbit.

IV. Shuttle Operations

The space shuttle is to be launched from two spaceports—Cape Canaveral, Florida, at 28.5 degree inclined orbits, and Vandenberg AFB, California, into polar orbits. If the shuttle is given a plane change capability of 31 degrees, inclination from zero (equatorial) to 59.5 degrees, and launches from VAFB can cover inclinations from 59 degrees to 149 degrees (retrograde). A plane change of this largest required magnitude could be accomplished in about 20 days at 1.5 degrees per day, which is a reasonable time for later Shuttle missions. For those missions with lesser orbital plane change required, less time must be spent in the plane-changing maneuver. The deployment and retrieval of the shuttle sail would require additionally[7] about 8 hours and 16 hours, respectively.

The Space Shuttle currently carries additional fuel for orbital maneuvering and stationkeeping. Any extra fuel carried to change the orbital plane would be an additional mass to be lifted by the Shuttle boosters. The use of the Shuttle sail would be an alternative for this extra mass; instead of extra fuel, the sail would be stowed in the cargo bay. As shown in Figure 6, the use of the Shuttle sail requires far less energy than the use of rocket propulsion. The use of the Shuttle sail in routine orbital plane changing and in orbital phasing would allow the use of the Shuttle for scavenging of the debris that now clutters low Earth orbit and presents a hazard to space flight.[15] This operation could be done during each mission that brought the Shuttle within sail range of a known piece of space debris. The sail could be deployed while the Shuttle crew was engaged in other operations, and when the sail brought the Shuttle into the proper position, the debris could be secured in the cargo bay for disposal or for preservation in a museum.

V. A Shuttle-Tethered Hypersonic Research Facility

A further use of the satellite-tethered lifting body would be in gaining fundamental knowledge of the flight conditions at about 100 km altitude and Mach 25. A variety of airfoils or lifting bodies could be instrumented and controlled to provide data over different angles of attack, atmospheric densities, and relative velocities. The regime of operation would encompass extremely long mean free paths for the air molecules and would allow new fundamental aerodynamic data to be obtained. As such a facility, the satellite-tethered lifting body would in essence function as a high-Mach-number, low-pressure wind tunnel for a variety of experimental investigations. In this mode of operation the lift vector would be oriented vertically, so as to provide an upward force on the satellite. This force would counteract some of the drag force tending to lower the satellite orbit. In this configuration, the airfoil need not be symmetric, and it might be equipped with a vertical stabilizer. The vertical stabilizer is not needed in the horizontal lift mode for yaw stability, which is provided by the tether.

The use of the Shuttle-tethered research airfoil or lifting body would be much simpler than changing its orbit plane. The airfoil would be oriented to provide a vertical lift force, thus maintaining the body almost directly below the Shuttle. There would be no need to change the length of the tether during the experiments except for slow changes in altitude to measure flight parameters at different atmospheric densities. There would be fewer dynamic response problems of the tether/sail system, and the retrieval could be a leisurely operation to prevent undue buildup of tether/sail oscillations.

VI. Conclusions

The concept of changing the orbital inclination of a satellite by an airfoil suspended into the atmosphere has been examined. The technique is potentially more efficient than the rocket or the synergetic maneuver for all inclination changes, but it is comparatively slow. Maximum rates of orbital precession of about 1.5 degrees per day appear to be achievable with a light Shuttle, a large, high-lift airfoil, and a high-temperature tether. The Shuttle sail could be folded and stowed in the cargo bay for re-use on a variety of satellite-servicing missions. The concept would also allow the use of the Space Shuttle for long-duration hypersonic aerodynamic studies for a variety of airfoils or lifting bodies at about 100 kilometers altitude and Mach 24. Further study is needed to define the optimum sail size and mass as functions of the Shuttle altitude, inclination change required, and required mission time.

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Table 1 Design Parameters for a Satellite Sail

Satellite Mass (Space Shuttle)	70,000 kg
Satellite Orbit Radius	6563 km
Precession Rate	1.5 deg/day
Sail Orbit Radius	6471 km
Tether Length	92-109 km
Tether Angle	9-27 deg
Orbital Period	88 min
Airfoil Area	100 sq m
Airfoil Structural Mass	700 kg
Airfoil Insulation	627 kg
Airfoil Equipment	173 kg
Airfoil Total Mass	1500 kg
Lower Tether Mass, A-286 Hi-Temp Alloy	364 kg
Upper Tether Mass, 302 Stainless	535 kg
Lower Tether Diameter	1. 72 mm
Upper Tether Diameter	0. 99 mm
Maximum Angle of Attack	10 deg
Maximum Lift Force	329 N
Maximum Drag Force (Including Tether)	110 N
Lift/Drag	3.0
Airfoil Dynamic Pressure, Q	54.4 N/sq m

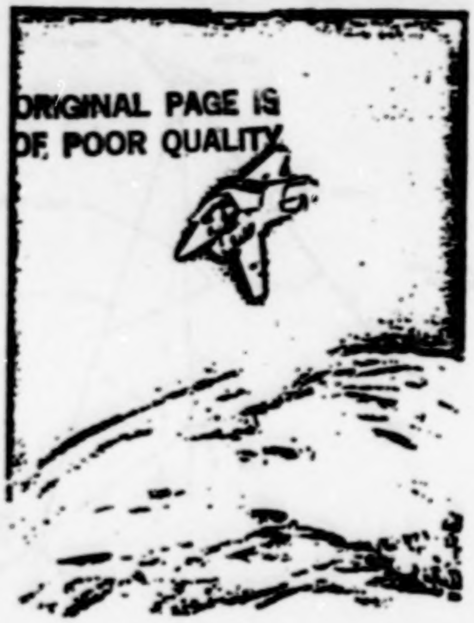
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Figure 1. An Artist's Concept of the Satellite Sail.

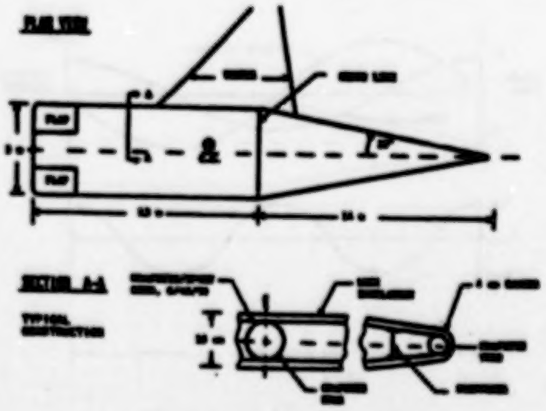

Figure 2. Schematic Diagram of the Airfoil Planform and Typical Cross-Section.

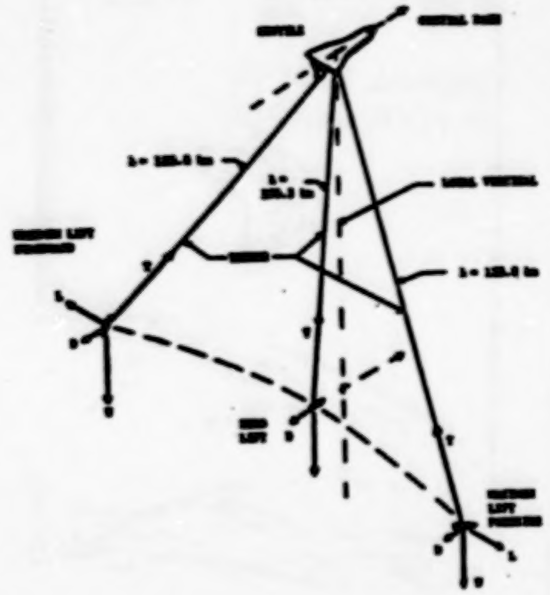

Figure 3. Shuttle, Tether, and Airfoil Geometry, and Maximum Excursion over One Orbit.

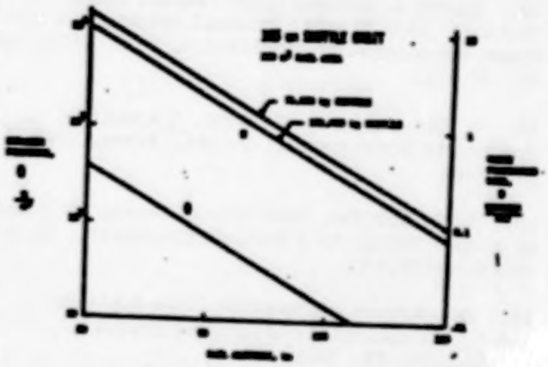

Figure 5. Dynamic Pressure and Shuttle Precession Rate for a 100-Square-Meter Sail.

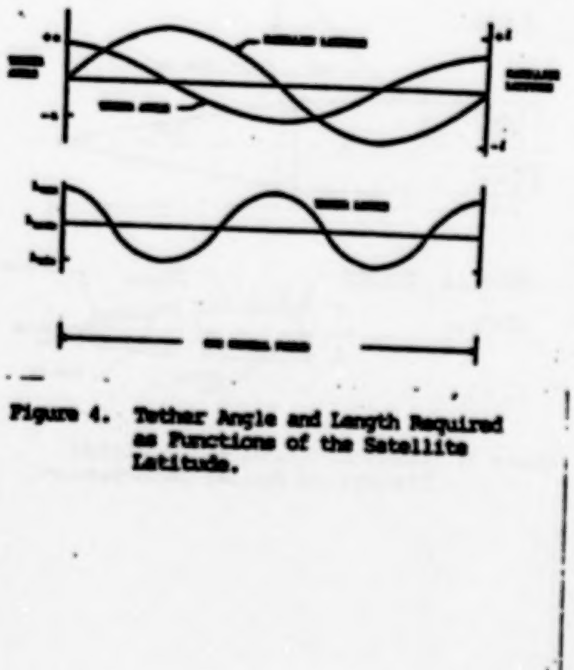

Figure 4. Tether Angle and Length Required as Functions of the Satellite Latitude.

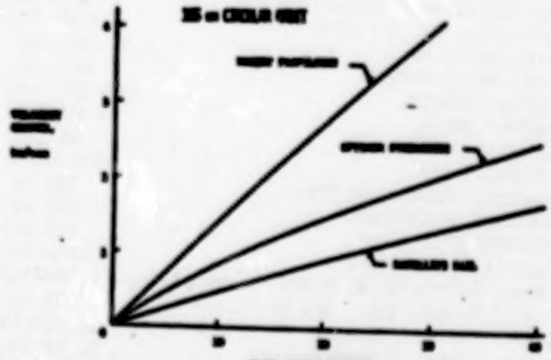

Figure 6. Required Velocity Changes for Three Different Plane-Change Techniques.

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PRESENTATION 6

TEST AND TECHNOLOGY

Stephen Graff, JPL

MISSION: TETHER A POWER PLANT TO A MANNED OR UNMANNED VEHICLE (SP100 FOR EXAMPLE)

PROBLEMS:

- ORBITAL MAINTAINANCE_ MUST WE SHUT DOWN POWER PLANT AND RETRIEVE FOR EVERY MANEUVER?
- CAN WE MANEUVER WITHOUT RETRIVAL?
- TEMPERATURE AND RADIATION TOLERENCE OF THE TETHER AND TETHER MECHANISM.
- HOW CAN THE CABLE BE CONSTRUCTED FOR RELIABILITY AND LONG MISSION LIFE?

NEED: A DYNAMIC MODEL WITH CONTROL LAWS TO HANDLE ROTATING OR RECIPROCATING MACHINERY ON A TETHER.

APPENDIX A

ATTENDEES

List of Attendees

Adornato, Rudolph	Grumman Aerospace
Aiken, Richard	University of Utah
Arrington, Jim	NASA Langley
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Benford, Susan	NASA Lewis
Bents, David	NASA Lewis
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	Robert Freitag
	Arthur Halenbeck
	Robert Hudson
	John E. Moye
	James Murphy
	Mark Nolan
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	Steven Lewis
	James McCoy
	Kenneth Kroll
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	Roy J. Duckett
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	Jack Price
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	Darrell Tenney
	Gerald Wallberg
	Maywood L. Wilson
	George Wood
NASA Lewis	Susan Benford
	David Bents
	Karl Faymon
	Patrick Finnegan
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	William Marshall
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	Uri Samir
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	Georg Von Tiesenhausen
	Peter H. Broussard

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Sperry	Ray Schneider
Stanford University	Roger Williamson
Systems, Science & Software	Don Parks
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The University of Michigan	George Carignan
TRW	Rim Kaminskas
	Jerome Wright
TRW Electronics & Defense Center	Carl Graves
University of British Columbia	V. Modi
University of Iowa	Gerry Murphy
University of Naples	Giovanni Carlomagno
	Luigi Napolitano
	Sergio Vetrella
University of Rome	Carlo Buongiorno
	Franco Mariani
University of Utah	Richard Aiken
Univ. of Dayton Res. Inst.	Nicholas Engler
	James Luers
USAF	Shore
	Peter Swan
USAF - Civil Service	Frederick Carley
USAF - Space Command	John Darrah
USAF - Space Tech Center	Norman Lee
Vought Corporation	Roy Cox
Wright Aeronautical Lab	Jerome Pearson
Wyle Laboratories	David Christensen

APPENDIX B

PANEL MEMBERS

ARTIFICIAL GRAVITY PANEL

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Dox Doxiadis	Rockwell
Dave Criswell	Calspace
Charles Tang	JPL
Dennis Fielder	NASA/JSC
John Gille	Martin Marietta
Paul Penzo	JPL
Ken Kroll	NASA/JSC
Luigi Napolitano	University of Naples
Troy Crites	Aerospace
Joe Tschirgi	McDonnell Douglas
Thomas Taylor	Taylor and Associates
Joe Carroll	Calspace
Klaus Reiwartz	ESA-ESTEC-Netherlands
David Yoel	Boeing Aerospace
Robert Conover	NASA Headquarters
Bryant Cramer	NASA Headquarters

CONSTELLATIONS PANEL

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Giovanni Rum, Co-Chairman	PSN/CNR, Italy
David J. Bents	NASA, Lewis Research Center
Georg von Tiesenhausen	NASA-MSFC
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APPENDIX C

AGENDA

Applications of Tethers in Space Workshop
Agenda
15-17 June 1983

14 June 1983-Tuesday	
6:00pm - 9:00pm	Registration
15 June 1983-Wednesday	
7:30am-8:30am	Registration
8:00am-8:30am	Panel Chairmen Meet
	Session I - Introduction
8:45am-9:15am	Welcome, Orientation and Prupose...Bob Marshall
9:15am-10:15am	Keynote Address...Ivan Bekey
10:15am-10:30am	BREAK
	Session II - Tethered Satellite System(TSS)
10:30am-10:45am	Project Overview...Jay Laue
10:45am-11:00am	Tether Deployment System...Donald Crouch
11:00am-11:30am	Satellite Overview...Gianfranco Manarini
11:30am-12:00pm	Satellite System Description...Marcello Vignoli
12:00pm-1:00pm	LUNCH
	Session III - Fundamentals and Applications
1:00pm - 2:00pm	Tether Fundamentals
2:00pm - 2:30pm	Science and Applications
2:30pm - 3:00pm	Electrodynamic Interactions
3:00pm - 3:15pm	BREAK
3:15pm - 3:45pm	Transportation Applications
3:45pm - 4:15pm	Artificial Gravity
4:15pm - 4:45pm	Constellations
4:45pm - 5:15pm	Technology and Test
6:00pm - 7:00pm	NO HOST BAR
7:00pm - 8:00pm	DINNER
8:00pm	Guest Speaker... Professor Giuseppe Colombo "Where Are We Going With Tethers?"

Applications of Tethers in Space Workshop (Cont.)

16 June 1983-Thursday	Session IV - Panel Meetings
8:00am - 8:30am	Charge to the Panels...Bob Marshall
8:30am - 12:00pm	Panels Meet - Assigned Rooms
12:00pm - 1:00pm	LUNCH
1:00pm - 4:00pm	Panels Meet - Assigned Rooms
4:00pm - 5:00pm	Plenary Session...Preliminary Panel Reports
17 June 1983-Friday	Session V - Panel Meetings Continued
8:00am - 11:00am	Panels Meet - Assigned Rooms
11:00am - 1:00pm	Plenary Session...Final Panel Reports
1:00pm - 2:00pm	LUNCH
	Session VI - Workshop Summary
2:00pm - 3:00pm	Panel Chairmen Meet
3:00pm - 4:30pm	Summary Recommendations of the Workshop
4:30pm	ADJOURN

APPENDIX D

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REFERENCES

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MAY 14 1985